

statistical cumulants derived from the received signals, the EGSV being indicative of a combination of signals received at the sensors from a signal source; and a supplemental computation module, for deriving output quantities of interest from the conditioned receiver signals and the EGSVs.

5        The basic invention as described in the preceding paragraph employs one of three basic methods for computing EGSVs: two iterative methods and one direct computation method. In the first iterative method, the system includes a linear combiner, for repeatedly computing a single channel combined signal from the conditioned receiver signals and an EGSV; means for supplying an initial EGSV to the

10      linear combiner, to produce the initial output of a single channel combined signal; an EGSV computation module, for computing successive values of the EGSV from successive values of the single channel combined signal received from the linear combiner and the conditioned receiver signals; and means for feeding the successive values of the EGSV back to the linear combiner for successive iteration cycles. Also

15      included is means for terminating iterative operation upon convergence of the EGSV to a sufficiently accurate value.

If the second iterative method is used, the system includes a cross-cumulant matrix computation module, for generating a matrix of cross-cumulants of all combinations of the conditioned receiver signals; a structured quadratic form computation module, for computing successive cumulant strength functions derived from successive EGSVs and the cross-cumulant matrix; means for supplying an initial EGSV to the structured quadratic form computation module, to produce the initial output of a cumulant strength function; an ESGV computation module, for generating successive EGSVs from successive cumulant strength functions received from the structured quadratic form computation module; means for feeding the successive values of the EGSV back to the structured quadratic form computation module for successive iteration cycles; and means for terminating iterative operation upon convergence of the EGSV to a sufficiently accurate value.

Finally, if the direct computation method is used, the system includes a

30      cross-cumulant matrix computation module, for generating a matrix of cross-cumulants

of all combinations of the conditioned receiver signals; and an EGSV computation module for computing the EGSV directly from the cross-cumulant matrix by solving a fourth degree polynomial equation.

Regardless which of the foregoing variants is employed, signal processing 5 may employ one of several different cumulant recovery (CURE) techniques. In a first of these techniques, the means for generating the set of conditioned signals includes a covariance matrix computation module, an eigendecomposition module for generating the eigenstructure of the covariance matrix and an estimate of the number of signal sources, and a transformation matrix for conditioning the receiver signals. An 10 EGSV generator then employs signals output by the eigendecomposition module to compute EGSVs. This technique is referred to in this specification as the eigenCURE or eCURE system.

An alternate processing technique uses covariance inversion of the received signals and is referred to as the CiCURE system. In this approach, the means 15 for generating the set of conditioned signals includes a covariance matrix computation module and a matrix decomposition module, for generating the inverse covariance matrix and a transformation matrix for conditioning the receiver signals. An EGSV generator then employs signals output by the eigendecomposition module to compute EGSVs. The system further includes a beamformer, for generating a recovered signal 20 from the receiver signals by using the EGSV(s) and the matrix obtained from the matrix decomposition module.

Yet another processing technique is referred to as pipelined cumulant recovery, or pipeCURE. The means for generating the set of conditioned signals includes a covariance matrix computation module, an eigendecomposition module for 25 generating an estimate of the number of signal sources, a transformation matrix for conditioning the receiver signals, and an eigenstructure derived from the receiver signals. Again, the EGSV generator employs signals output by the eigendecomposition module to compute EGSVs. Processing is on a block-by-block basis, and the system further comprises a multiple port signal recovery unit, including means for matching

current EGSVs with EGSVs from a prior data block to impose waveform continuity from block to block.

Another variant that can be used in any of these processing techniques involves the manner in which initial EGSVs are computed at the start of processing a new block of data. In accordance with this aspect of the invention, the initial values of EGSVs for each new processing block are computed by combining a prior block EGSV and a cumulant vector derived from the utility function used in the EGSV generator. More specifically, the means for combining takes the sum of the prior block EGSV multiplied by a first factor, and the cumulant vector multiplied by a second factor. The first and second factors may be selected to provide an initial EGSV that anticipates and compensates for movement of a signal source.

In a practical embodiment of the invention, the system functions to separate a plurality ( $P$ ) of received cochannel signals. If the first iterative method is employed, there are multiple EGSV generators ( $P$  in number), including  $P$  EGSV computation modules and  $P$  linear combiners, for generating an equal plurality ( $P$ ) of EGSVs associated with  $P$  signal sources. The supplemental computation module functions to recover  $P$  separate received signals from the  $P$  generalized steering vectors and the conditioned receiver signals. More specifically, the supplemental computation module includes a recovery beamformer weight vector computation module, for generating from all of the EGSVs a plurality ( $P$ ) of receive weight vectors, and a plurality ( $P$ ) of recovery beamformers, each coupled to receive one of the  $P$  receive weight vectors and the conditioned receiver signals, for generating a plurality ( $P$ ) of recovered signals.

For recovery of multiple signals using the second iterative method, there is a plurality ( $P$ ) of EGSV generators, including  $P$  EGSV computation modules and  $P$  structured quadratic form computation modules, for generating an equal plurality ( $P$ ) of EGSVs associated with  $P$  signal sources. Again, the supplemental computation module includes a recovery beamformer weight vector computation module, for generating from all of the EGSVs a plurality ( $P$ ) of receive weight vectors, and a plurality ( $P$ ) of

recovery beamformers, each coupled to receive one of the  $P$  receive weight vectors and the conditioned receiver signals, for generating a plurality ( $P$ ) of recovered signals.

If the direct processing method is used to separate two signals, the ESGV computation module generates two EGSVs from the cross-cumulant matrix data; 5 and the supplemental computation module functions to recover two separate received signals from the two generalized steering vectors and the conditioned receiver signals. The supplemental computation module includes a recovery beamformer weight vector computation module, for generating from both of the EGSVs two receive weight vectors, and two recovery beamformers, each coupled to receive one of the receive 10 weight vectors and the conditioned receiver signals, for generating two recovered signals.

Although the system of the invention operates in a "blind" sense, without knowledge of the geometry or calibration data of the sensor array, it will also function as a direction finder if array calibration data are available. Hence, in one 15 embodiment of the invention, the system functions to derive the direction of arrival (DOA) of a received signal; and the supplemental computation module includes a memory for storing sensor array calibration data, and means for deriving the DOA of a received signal from its associated steering vector and the stored sensor array calibration data. More specifically, the sensor array calibration data includes a table 20 associating multiple DOA values with corresponding steering vectors; and the means for deriving the DOA includes means for performing a reverse table lookup function to obtain an approximated DOA value from a steering vector supplied by the generalized steering vector generator. The means for deriving the DOA may also include means for interpolating between two DOA values to obtain a more accurate result.

25 In another important embodiment of the invention, the supplemental computation module of the signal processing system also includes a transmitter, for generating transmit signal beamformer weights from the received signal beamformer weights, and for transmitting signals containing information in a direction determined by the transmit signal beamformer weights.

Other aspects of the invention pertain to various application of the basic cumulant recovery (CURE) signal processing engine described above. Some of these applications are summarized in the following paragraphs.

An important application of the invention is in two-way radio communication. Because CURE processing generates an estimated generalized steering vector not necessarily for each received signal, but for each signal source, the invention provides an important benefit when used in multipath conditions. Signals reaching a receiving antenna array over multiple paths will be combined in the CURE system if the received components are coherent, and the resultant generalized steering vector represents the combined effect of all the coherent multipath signals received at the antenna. This feature has a number of advantages. First, a radio receiving system using the CURE system is inherently immune to multipath problems encountered by conventional receivers. Second, by using generalized steering vectors, there can be an associated generalized null in the antenna directivity pattern, which can be used to null out an interfering signal having multipath structure in favor of a cochannel signal from another source. Third, the signal recovery method provides a diversity gain in the presence of multipath components, such that a stronger combined signal is received as compared with a system that discards all but one component. Fourth, the generalized steering vector concept allows multiple cochannel signals to be received and transmitted in the presence of multipath effects. Fifth, cochannel signal sources that are collinear with the receiver sensor array can be received and separated if there are multipath components.

In another aspect of the invention, the CURE signal separation system can be used to separate signals transmitted in different modes over a "waveguide," by which is meant any bounded propagation medium, such as a microwave waveguide, an optical waveguide, a coaxial cable, or even a twisted pair of conductors. Although the transmission modes may become mixed in the waveguide, the original signals are easily recovered in the CURE system.

In still another aspect of the invention, the CURE signal separation system can be used to separate signals recorded on closely space tracks on a recording

medium. Crosstalk between the signals on adjacent tracks is eliminated by using the CURE system to effect recovery.

In yet another aspect of the invention, the CURE signal separation system can be used to extend the effective dynamic range of a receiver system.

5 In a further aspect of the invention, the CURE signal separation system can be used to perform a complex phase equalization function automatically, without knowledge of the amount of phase correction that is needed.

The CURE system may be modified to compensate for moving signal sources, and may also be modified to handle a wideband signal separation problem.  
10 The wideband signal separator includes multiple narrowband CURE systems, means for decomposing a wide band of signals into multiple narrowbands for processing, and means for combining the narrow bands again.

Other aspects and advantages of the invention will become apparent from the following more detailed description, taken together with the accompanying  
15 drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a taxonomy diagram depicting the interrelationships of the  
20 invention's various cochannel signal processing methods.

FIG. 2A is a block diagram of the cumulant recovery (CURE) system of the invention in general form, depicting a first iterative method.

FIG. 2B is a block diagram similar to FIG. 2A, but depicting a second iterative method.

25 FIG. 2C is a block diagram similar to FIG. 2A, depicting a direct computation method.

FIG. 3A is a block diagram similar to FIG. 2A, but modified to depict how the invention functions to separate multiple received cochannel signals.

30 FIG. 3B is a block diagram similar to FIG. 3A, but depicting the first iterative method.

FIG. 3C is a block diagram similar to FIG. 3A, but depicting the direct computation method.

FIG. 4A, is a block diagram of a supplemental computation module for signal recovery, shown in FIGS. 3A, 3B and 3C.

5 FIG. 4B is a block diagram of a supplemental computation module for use in conjunction with the system of FIGS. 2A, 2B or 2C, to provide a direction finding function.

FIG. 5 is a block diagram similar to FIG. 2A, but modified to depict a receiver/transmitter function.

10 FIG. 6 is a block diagram similar to FIG. 3A, but modified to show input of signals from a signal "waveguide."

FIG. 7 is a block diagram showing in more detail the functions performed in accordance with the two iterative methods for cochannel signal separation and recovery.

15 FIG. 8A is simplified block diagram of a cochannel signal recovery system in accordance with the present invention.

FIG. 8B is a hardware block diagram similar to FIG. 8A, of one preferred embodiment of the invention.

20 FIG. 9 (comprising FIGS. 9A and 9B) is another block diagram of the system of FIG. 7, with some of the subsystem functions recited in each of the blocks.

FIG. 10 is a block diagram of the preprocessor computer of FIG. 7.

FIG. 11 (comprising FIGS. 11A and 11B) is a block diagram of a signal extraction port in an active state.

25 FIG. 12 is a block diagram of the multiple port recovery unit of FIG. 9, including multiple signal extraction ports and an orthogonalizer.

FIG. 13 (comprising FIGS. 13A, 13B and 13C) is a block diagram of the signal recovery controller of FIG. 7.

FIG. 14 is a block diagram of a signal extraction port in the inactive state.

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FIG. 15 is a block diagram of signal recovery system using covariance inversion cumulant recovery (CiCURE).

FIG. 16 is a block diagram of a signal extraction port in the active state using the CiCURE system illustrated in FIG. 15.

5 FIG. 17 is a block diagram of an alternate embodiment of the invention referred to as pipeCURE.

FIG. 18 is a schematic diagram depicting a processing difficulty associated with moving signal sources.

FIGS. 19 and 20 are vector diagrams depicting the effect of using  
10  $\alpha$ - $\beta$ CURE and  $\mu$ CURE updating to initialize a block of samples for eCURE processing in the moving source situation such as shown in FIG. 18.

FIG. 21 is a schematic diagram showing an overload condition in which there are more signal sources than antenna elements.

15 FIG. 22 is a diagram of an antenna array directivity pattern for handling the situation shown in FIG. 21.

FIG. 23 is a schematic diagram depicting multipath propagation paths from a transmitter to a receiver array.

FIG. 24 is a schematic diagram depicting how the system of the invention handles coherent multipath signals in the presence of interference.

20 FIG. 25 is a schematic diagram depicting how the system of the invention handles non-coherent multipath signals in the presence of interference.

FIG. 26 is a schematic diagram depicting how the system of the invention handles receiving a desired signal in the presence of an interference signal with multipath components and a second interference source.

25 FIG. 27 is a schematic diagram depicting the invention as used in the recovery of a received signal in the presence of a strong local transmitter.

FIG. 28 is a schematic diagram depicting the invention as used in the recovery of a weak received signal in the presence of a strong jamming signal located nearby.

FIG. 29 is a schematic diagram depicting portions of a cellular telephone communication system of the prior art.

FIG. 30 is a schematic diagram depicting how a communication system of the prior art separates cochannel signals.

5 FIG. 31 is a schematic diagram depicting how the present invention operates in the environment of a cellular telephone communication system.

FIG. 32 is a block diagram showing major portions of a transmitter as used in conjunction with the system of the present invention.

10 FIG. 33 is a block diagram showing a transmitter similar to the one in FIG. 32, but with more detail of some aspects of the apparatus.

FIGS. 34A and 34B are diagrams depicting operation of the invention in recovery of dual-polarized signals.

FIG. 35 is a schematic diagram depicting the invention as used in conjunction with an optical fiber network.

15 FIG. 36 is a schematic diagram depicting the invention as used in copy-aided direction finding.

FIG. 37 is a schematic diagram depicting the invention as used in extending the dynamic range of a receiver.

20 FIG. 38 is a schematic diagram depicting the invention as used in disk recording system.

FIG. 39 is a schematic diagram depicting the invention as used to effect automatic phase rotation equalization of a QAM signal.

FIG. 40A is a signal constellation diagram for a QAM system with four amplitude-phase states by way of illustration.

25 FIG. 40B is a diagram similar to FIG. 40A, showing a phase rotation of  $\theta$  as a result of propagation of the signal to the receiver.

FIG. 41 is a block diagram showing extension of the cumulant recovery system of the invention to cover a wide frequency band.

**DESCRIPTION OF THE PREFERRED EMBODIMENTS****1.0 Introduction:**

Because the present invention encompasses a number of different but related concepts and applications, and because the key signal processing concepts of the invention can be implemented in several different embodiments, this detailed description is divided into sections and subsections, each of which covers a different specific embodiment or practical application of the invention. The following is a table of contents of this description of the preferred embodiments:

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## 2.0 Overview of the Concept of the Invention:

The present invention resides in a system and method for processing signals received by a sensor receiving system having an array of sensor elements. The system is capable of receiving and processing a signal from a single source, and for 5 purposes of explanation the system will sometimes be described as receiving and processing just one signal. It will, however, shortly become clear that the system is capable of, and best suited for, receiving and processing signals from multiple sources, and that the multiple signals may utilize overlapping signal frequency bands as viewed at the receiver, i.e. they may be cochannel signals. As discussed above in the 10 "background of the invention" section, detection and processing of cochannel signals presents difficulties that have not been adequately addressed by signal processing systems of the prior art.

One central concept that makes the various aspects of overall invention possible is the ability to determine accurate estimates of generalized steering vectors of 15 the source signals incident on a sensor array or, more generally, estimates of the linear combinations that represent the relative amplitudes of the source signals in each channel of a multichannel signal stream. The meaning of the term "generalized steering vector" will become better understood as this description proceeds. A definition for present purposes is that the generalized steering vector associated with a particular 20 signal source represents the weighted sum of ordinary steering vectors corresponding to all multipath components of signals from that source. An ordinary steering vector is the value of the array manifold at a single angle corresponding to a source's DOA. Multipath components arise when a signal from a single source reaches a receiver over multiple propagation paths.

25 The invention encompasses three distinct methods for determining estimates of the generalized steering vectors of source signals. FIG. 1 illustrates the taxonomy and relationships among the methods. Two of the methods for determining the estimated generalized steering vectors (EGSVs) involve iterative computations. The first of these, indicated by reference numeral 10, is called the "beamform - cross- 30 cumulant" method. In this method, an initial EGSV is iteratively updated and

improved by a method that involves using the initial EGSV as a complex weight vector in a linear beamformer that operates on sensor signals (i.e., signal measured at a sensor array, to be discussed shortly with reference to other drawing figures). Cross-cumulants are computed, specifically between the output signal from the beamformer 5 used in this method and each of the beamformer's input signals.

The term "cumulant" is defined more completely in later sections of this specification, but for purposes of this general discussion it is sufficient to note that cumulants are fourth-order (or higher even-order) statistical moments of the received signals. The cross-cumulants are formed into a vector which, upon normalization, 10 becomes the next EGSV. This iteration cycle is repeated until convergence is attained, based on a predefined convergence test or on a selected number of iteration cycles. Upon convergence, the EGSV will have converged to the generalized steering vector of one of the incident source signals.

The second iterative method for obtaining EGSVs is referred to as the 15 "C- matrix" method and is indicated at 12 in FIG. 1. In this method, a particular matrix of cross-cumulants among the sensor signals is calculated first, before the iterative process starts. There are no subsequent calculations of cumulants within the iterative cycle. Instead, an initial EGSV is used to calculate a structured quadratic form, which yields a quantity called "cumulant strength." The EGSV is adjusted to 20 maximize the cumulant strength by means of an iterative optimization procedure. Upon convergence, the EGSV will have converged to the generalized steering vector of one of the incident source signals.

The third method of finding the EGSVs is non-iterative. It is referred to as the "direct computation" or "analytic" method and is indicated at 14 in FIG. 1. This 25 method can only recover up to two incident signals, but is unrestricted as to the number of sensor array elements or processing channels. The method first computes the same matrix of cross-cumulants among the sensor signals as is used in the second iterative method. However, a fourth degree polynomial equation is solved instead of optimizing a structured quadratic form. The solutions to the fourth degree polynomial yield the 30 final EGSVs directly without iteration.

In addition to the three methods for generating the EGSVs of the source signals, the present invention has three alternative basic algorithmic structures on which the preferred embodiments of the invention are based. FIG. 1 shows diagrammatically that the EGSVs generated by either of the three methods (10, 12 or 5 14) are coupled over line 16 to a selected one of three algorithmic structures 18, referred to as CiCURE, eCURE, and pipeCURE. As will be further explained below, the acronym CURE stands for cumulant recovery. The terms CiCURE, eCURE and pipeCURE refer to specific embodiments of the invention known as covariance inversion CURE, eigenCURE and pipelined CURE, respectively. Each structure 10 encompassed by the block 18 in FIG. 1 can employ any of the three methods (10, 12 or 14) described above for determining the source signal EGSVs.

By way of example, a subsequent section of this specification (Section 3.0) describes a preferred embodiment consisting of the eCURE algorithmic structure and the beamform - cross-cumulant method. Another section (Section 5.0) details a 15 preferred embodiment consisting of the pipeCURE structure and the C-matrix method. However, all other combinations are possible and may be preferable depending on the specific engineering application.

The algorithmic structures (18) are described below in subsequent descriptive sections as processing input samples in a "batch processing" mode, meaning 20 that sampled data from the sensor signals are grouped into blocks of samples, which are then processed one block at a time. The block size is arbitrary and is not intended to limit the scope of the present invention. For example, the block size can be as small as one, in which case, the batch mode reduces trivially to "sample-by-sample" processing.

25 In some situations, the EGSVs of the source signals vary with time, due, for example, to changing geometric relationships among the locations of the sources, the receiving sensor array, or multipath reflectors. For such situations, two methods are presented for determining the initial EGSVs for each block of samples. These methods incorporate a technique known as  $\alpha$ - $\beta$  tracking into the block initialization 30 process and thereby make the acquisition, capture, separation, and recovery of source

signals more stable when any of the sources or the receive sensor array is moving. Two block initialization methods are presented for this purpose and are called  $\alpha$ - $\beta$ CURE and  $\mu$ CURE. As indicated by block 19 in FIG. 1, these two methods are applicable to any of the basic algorithmic structures 18.

5 FIG. 2A shows the system of the present invention in general form, employing the first iterative method referred to above as the beamform - cross-cumulant method. The system includes four principal components: a sensor receiving system 20, an estimated generalized steering vector (EGSV) computation module 22, a supplemental computation module 24 and a linear combiner 26.

10 The sensor receiving system 20 includes components not shown in FIG. 2A, but which will be discussed in more detail below, including an array of sensors to convert incident signals into electrical form, and some form of signal conditioning circuitry. In each of the embodiments and applications of the invention, incident signals 27 are sensed by the sensor receiving system 20 and, after appropriate 15 processing, the supplemental processing module 24 generates desired output signals or parameters as needed for a specific application of the invention. For example, in a signal separation application, the output signals will be the reconstructed cochannel signals received from separate signal sources. An important aspect and advantage of the invention is that the received signals may be of any modulation or type.

20 A key component of the signal processing system of the invention is the estimated generalized steering vector (EGSV) computation module 22, which receives the conditioned received signals over line 28 from the sensor receiving system 20, and computes an EGSV from the conditioned signals. The EGSV, in accordance with the invention, results in optimization of a utility function that depends on fourth or higher 25 even-order statistical cumulants derived from the received signals. At this point in the description, cumulants have not yet been defined, but they are discussed in Section 4.0. For the present, it is sufficient to note that cumulants are fourth-order (or higher even-order) statistical moments of the received signals.

30 The EGSV computation module 22 functions in an iterative manner in cooperation with the linear combiner 26. The linear combiner 26 begins a first iteration

with an initial EGSV, indicated at 30, which may be an estimate or simply a random initial vector quantity. The linear combiner 26 then combines the received signals on line 28 with the initial EGSV and generates a single-channel combined signal on line 32 to the EGSV computation module 22. The latter performs its cumulant computation and 5 generates a revised EGSV, which is fed back to the linear combiner 26 over line 34. The iterative process continues until the EGSV has converged to an appropriately accurate solution, which is output to the supplemental computation module 24 over line 36. The output on line 36 is also referred to as an estimated generalized steering vector, which closely approximates the actual generalized steering vector and 10 represents the weighted sum of ordinary steering vectors corresponding to all multipath components of signals from a source. Where no multipath components are present, the generalized steering vector reduces to an ordinary steering vector for the source. However, the term "generalized" steering vector is used frequently in this specification, to convey the meaning that the steering vector generated automatically 15 and dynamically takes into account the possibility of receiving a signal over multiple paths.

The function of the supplemental computation module 24 depends on the specific application of the invention. This module makes use of the conditioned received signals on line 28 and the generalized steering vector on line 36, and 20 generates the desired output signal or parameters on output line 38.

It should be understood that the components shown in FIG. 2A, and in particular the EGSV computation module 22 and the linear combiner 26, function to generate a single estimated generalized steering vector on line 36, corresponding to a single signal source from which signals are received at the sensor receiving system 20. 25 In a number of applications, as will be further described, multiple linear combiners 26 and multiple EGSV computation modules 22 will be needed to separate signals from multiple sources. Similarly, in most applications the supplemental computation module 24 must also be replicated, at least in part, to generate multiple desired output signals.

Another aspect of FIG. 2A to keep in mind is that it is an imperfect 30 attempt to depict a number of the invention's many possible forms in a single

conceptual diagram. The concept of the generalized steering vector is central to all forms of the invention. The estimated generalized steering vector (EGSV) provides a means for tracking sources through time free of discontinuity. The estimated generalized steering vector computational module, 22 in FIG. 2A, may be partially 5 merged with the supplemental computation module 24 or the order of computation modified to accommodate physical implementation. This is true in the case of a specific implementation of a signal recovery system, described subsequently, in which recovered signals are generated as outputs of the supplemental computation module 24.

An important aspect of the invention is that the EGSV computation 10 module 22, or multiple modules in some embodiments, compute estimated generalized steering vectors extremely rapidly, either by direct computation or by an iterative process that converges superexponentially. Moreover, each EGSV represents the weighted sum of steering vectors associated with multipath components derived from a single signal source. As will be described in the next descriptive subsection, multiple 15 EGSVs can be conveniently processed to reconstruct and separate signals from multiple signal sources.

As the description of the various embodiments proceeds, it will become apparent that certain components of the invention are common to many applications. In terms of the components shown in FIG. 2A, the common components include the 20 EGSV computation module 22, the linear combiner 26 and signal conditioning portions of the sensor receiving system 20. Accordingly, in many instances it would be advantageous to fabricate these components as a monolithic semiconductor device or chip, to be mounted in close association with other components in the supplemental computation module 24, which vary by application. Alternatively, a set of 25 semiconductor chips could include various embodiments of the supplemental computation module 24, such as for signal separation, direction finding and so forth.

FIG. 2B illustrates the form of the invention that uses the second iterative method (12, FIG. 1), called the C-matrix method, for generating EGSVs. It will be observed that the figure is similar to FIG. 2A, except that there is no linear

combiner. Instead there is a cross-cumulant matrix computation module 40 and a structured quadratic form computation module 42.

The cross-cumulant computation module 40 receives conditioned sensor signals over line 28 from the sensor receiving system 20, computes the cross-cumulants 5 of all combinations of the sensor signals and stores the results in a matrix having a particular mathematical structure. This matrix of cross-cumulants, denoted  $C$ , has dimensions  $P^2 \times P^2$ , where  $P$  is the number of signal sources, and is stored for subsequent computations. This  $C$  matrix is computed before any iterative computations 10 are performed, and it will be noted that the EGSVs fed back from the EGSV computation module 22 over line 34 are coupled to the structured quadratic form computation module 42 and not to the cross-cumulant matrix computation module 40.

The structured quadratic form computation module 42 is used in an iterative computational loop that, starting with an initial estimated generalized steering vector (EGSV) on line 30, produces a series of successively improved values for the 15 EGSV, until a termination test is satisfied. In each cycle of the iterative loop the module 42 receives an input EGSV and outputs a cumulant strength function (on line 32), which is obtained by computing a structured quadratic form involving the  $C$  matrix and the input EGSV. The mathematical details of the computation are described in a later section. The cumulant strength function, so obtained, is output to the EGSV 20 computation module 22 to update the EGSV. As in FIG. 2A, the nature of the supplemental computation module 24 in FIG. 2B depends on the particular application of the invention.

The EGSV computation module 22 together with the structured quadratic form computation module 42 are part of an iterative computational loop that 25 produces a series of successively improved values for an EGSV of a source signal, starting from an initial value. The EGSV computation module 22 receives as input a cumulant strength value for the current value of an EGSV. Based upon this cumulant strength, the module 22 determines a new value for the EGSV that will cause the value of the cumulant strength value to increase in absolute value. This new EGSV is output

to the structured quadratic form computation module, where it replaces the old EGSV, and the computation cycle is repeated until a termination test is satisfied.

FIG. 2C depicts the direct computation method of the invention in conceptual form using the same basic structure as FIGS. 2A and 2B. The EGSV computation module in this figure is referred to by numeral 22', since it performs its function differently from the module 22 in FIGS. 2A and 2B. The EGSV computation module 22' receives as input the C matrix computed by the cross-cumulant matrix computation module 40. The EGSV computation module 22' computes the solutions to a fourth degree polynomial equation, from which the EGSVs of one or two sources are directly determined. The mathematical details of the particular polynomial equation are described in a Section 7.0. The values of the EGSVs, so determined, are output to the supplemental computation module 24.

It will be understood that FIGS. 2A, 2B and 2C illustrate the processing required to recover a single source signal from among a plurality of possible source signals, for purposes of explanation. We will now turn to the case of recovery of multiple signals.

## 2.1 Signal Separation Concept:

The present invention has a number of applications in the communications field and, more specifically, in the separation of cochannel signals. FIG. 3A illustrates the concept of signal separation using the first iterative method (10, FIG. 1) and differs from FIG. 2A in that there are multiple linear combiners 26.1 through 26.P and multiple estimated generalized steering vector (EGSV) computation modules 22.1 through 22.P. The supplemental computation module 24 has been replaced by a supplemental computation module 24A for signal recovery, the details of which will be explained with reference to FIG. 4A. The sensor receiving system 20 outputs the received signals in conditioned form on line 28, which is connected to each of the linear combiners 26 and EGSV computation modules 22. Signal conditioning in the sensor receiving system, 20, which is described subsequently, may be used to transform the received signals to  $P$  sets of signals, where  $P$  is the number of signal

sources being received, and to be separated. As in FIG. 2A, the EGSV computation modules 22 and the linear combiners 26 cooperate to produce converged values of estimated generalized steering vectors on output lines 28.1 through 28.P. The supplemental computation module 24A uses these generalized steering vectors and the 5 received signals on lines 28 to generate  $P$  separate recovered signals on lines 38. How this latter step is accomplished is best understood from FIG. 4A, which will be discussed after consideration of FIGS. 3B and 3C.

FIG. 3B depicts a cochannel signal separation and recovery system similar to that of FIG. 3A, but using the second iterative method (12, FIG. 1). As in 10 FIG. 2B, there is a single cross-cumulant matrix computation module 40 but, unlike the FIG. 2B system, there are multiple ( $P$ ) structured quadratic form computation modules 42.1, 42.2 ... 42.P, each of which receives cross-cumulants from the matrix computation module 40 and conditioned input signals from line 28. Cumulant strength values generated by the structured quadratic form computation modules 42 are supplied 15 to respective EGSV computation modules 22.1, 22.2 ... 22.P, which output recomputed EGSVs for feedback over lines 34.1, 34.2 ... 34.P, respectively, to the structured quadratic form computation modules 42.1, 42.2 ... 42.P, and converged values of the EGSVs on lines 36.1, 36.2 ... 36.P.

FIG. 3C depicts a signal separation and recovery system similar to those 20 of FIGS. 3A and 3B, but using direct computation instead of an iterative method. This figure is also closely similar to FIG. 2C, except that the ESGV computation module 22' generates two EGSVs on output lines 36.1 and 36.2, and supplemental processing is performed in the supplemental computation module for signal recovery, which generates two recovered signals for output on lines 38.1 and 38.2.

25 As shown in FIG. 4A, the supplemental computation recovery module for signal recovery 24A includes a recovery beamformer weight vector computation module 44 and multiple recovery beamformers 46.1 through 46.P. Computation of the weight vectors in module 44 is made in accordance with a selected known technique used in signal processing. The beamforming weight vectors for signal recovery are 30 computed directly from the generalized steering vectors. This is done by one of two

methods: (1) by projecting each generalized steering vector into the orthogonal complement of the subspace defined by the span of the vectors of the other sources by matrix transformation using the Moore-Penrose pseudo-inverse matrix; or (2) by using the Capon beamformer, also called the Minimum Variance Distortionless Response 5 (MVDR) beamformer in the acoustics literature. The module 44 generates, from the  $P$  input estimated generalized steering vectors (EGSVs), a set of  $P$  weight vectors  $w_1$  through  $w_P$ , on lines 48.1 through 48.P. Implicit in the function performed by the module 44 is the orthogonalization of the output signals, such that the weight vectors are mutually orthogonal, i.e. each is representative of a separate signal. Alternatively, 10 the module 44 may be implemented in the manner described in Section 3.0.

The weight vectors  $w_1$  through  $w_P$  are applied to the received, conditioned signals on line 28, in the recovery beamformers 46.1 through 46.P. This is basically a process of linear combination, wherein each signal component is multiplied by a corresponding component of the weight vector and the results are added together 15 to produce one of the recovered signals.

As will be seen from the more detailed description of the preferred embodiments, the functions of the linear combiners 26 (in the case of FIG. 3A), the EGSV computation modules 22, the recovery beamformer weight vector computation module 44 and the recovery beamformers 46 may be combined in various ways. 20 Moreover, all of these functions, together with signal conditioning performed in the sensor receiving system 20, may be conveniently implemented in one or more integrated circuits.

## 2.2 Signal Separation Concept in the Multipath Environment:

25 As will be later described in more detail, signal separation in accordance with this invention has important advantages in the context of multipath signal processing. Communication signals, particularly in an urban environment, often reach a receiver antenna over multiple paths, after reflection from geographical features, buildings and other structures. The multiple signals arrive at the antenna with different 30 signal strengths and subject to relative time delays and other forms of distortion.

Because they arrive from different directions, such signals may be separated in a conventional cochannel signal separation system. However, the cochannel signal processing system of the present invention will automatically combine the multipath components if they are still coherent with each other. Coherency, in this context, is a 5 relative term that simply indicates the degree to which the signals are identical. Multiple signals are classified as coherent if they are relatively similar to each other, as measured by a cross-correlation function over a finite time interval. Multipath components are noncoherent, and therefore not combinable, when they suffer large relative time delays or when a signal transmitter or receiver is in motion, causing a 10 Doppler shift in the transmitted signal that affects one path more than another.

The key to successful processing of multipath components is that each generalized steering vector referred to with reference to FIGS. 1, 2A-2C and 3A-3C corresponds to the sum of all of the mutually coherent multipath components of a signal source incident on the sensor receiving system 20. The generalized steering 15 vectors from all signal sources are then converted to a set of beamforming weight vectors (in recovery beamformer weight vector computation module 44), without the need for knowledge of array geometry or array manifold calibration data (which relates array steering vectors with angles of arrival for a particular array). For many of its applications, the invention is, therefore, completely "blind" to the array manifold 20 calibration data and the physical parameters of the array.

### 2.3 Direction Finding Concept:

The invention as described with reference to FIGS. 2A-2C, 3A-3C and 4A provides for cochannel signal separation, even in a multipath environment, without 25 use of specific sensor array manifold information. The array parameters, and specifically array calibration data that relate array steering vectors with directions of signal arrival, are needed if one needs to know the angular directions from which signals are being received. FIG. 4B illustrates this concept for a single signal source referred to as source  $k$ . Although the concept depicted in FIG. 4B is conventional, the 30 manner in which the present invention generates the input steering vectors is novel. A

generalized steering vector, referred to as  $\underline{a}_k$ , is received from one of the EGSV computation modules 22.k (FIG. 3A) on line 36.k and is processed in a direction of arrival (DOA) search module 24B, which is a specific form of the supplemental computation module 14 (FIGS. 2A-2C). The DOA search module 14B uses stored 5 array calibration data 50, which associates each possible direction of arrival with a steering vector. These calibration data are typically stored in a memory device as a lookup table. In the DOA search module 24B, a reverse table lookup is performed to obtain the two closest directions of arrival from the input steering vector, as indicated in block 52. Then a more precise angle of arrival is obtained by performing an 10 interpolation between the two angle values retrieved from the calibration data 50, as indicated in block 54. The direction of arrival (DOA) parameter for the  $k^{\text{th}}$  signal source is output from computation module 24B on line 38.k.

#### 2.4 Transmitter/Receiver Concept:

15 As will be discussed further in section 12.0, an important application of the invention is to two-way communication systems. In many communication systems, the allocation of transmission frequencies within a geographical area, such as in a predefined cell in a cellular telephone system, is often a limiting factor that determines the maximum number of active users that the system can handle. In accordance with 20 this aspect of the present invention, information derived from signals received and separated in a receive mode of operation are used to generate signals to a transmit antenna array, in such a way that separate information signals can be transmitted to respective remote stations using the same frequency.

25 As already discussed, the present invention makes use of an array of sensors or antennas to separate received signals of the same frequency (cochannel signals). In a two-way communication system of the type having multiple mobile units, it would be impractical, in general, to require the use of an antenna array at each remote or mobile transmitter/receiver. These remote units may be installed in vehicles or be hand-held devices for which the use of an antenna array is either inconvenient or 30 simply impossible. However, in most communication systems, the communication path

between remote units is completed through one or more base stations operating as a receiver and transmitter. Since the base stations are generally larger and more powerful than the mobile units and are fixed in location, they may be conveniently structured to include antenna arrays for both receiving and transmitting. As discussed above, a 5 receive array connected to the system of the invention provides for separation of received cochannel signals. Moreover, an important by-product of the signal separation process is a set of generalized steering vectors, each associated with a separate signal source.

As shown in FIG. 5 for a single remote transmitter/receiver station, 10 received signals are recovered on line 38, in the manner discussed with reference to FIG. 2A. In a two-way communication system, a transmitter 56 uses the generalized steering vector corresponding to the received signal source, obtained from the EGSV computation module 22, in order to generate a weight vector for application to a transmit antenna array (not shown). The transmitter 56 also receives, on line 58, an 15 information signal to be transmitted. Typically, this will be in the form of a digitized voice signal, although it may be a data signal of some other type. The transmitter 56 generates the transmit weight vector in accordance with a technique to be described below in Section 12.0, modifies the information signal in accordance with the weight vector, modulates a carrier signal with the weighted information signal components, 20 and sends a set of signals to the transmit array, as indicated by lines 60. The carrier frequency, although the same for each of the transmitted cochannel signals, is usually selected to have a frequency different from the receive signal frequency. As will also be further discussed below, in the more general case of multiple received signals and multiple transmitted signals, the transmitter 56 generates multiple weight vectors, 25 which are applied to the respective information signals to be transmitted, then linearly combined, antenna element by antenna element, and finally modulated to produce a set of composite antenna element signals for coupling to the transmit antenna array.

It will be appreciated that this aspect of the invention provides a simple but effective technique for use in a communication system base station, for receiving 30 cochannel signals from, and transmitting cochannel signals to, multiple remote stations

in close proximity to a base station and to each other. Limited only by the number of elements in the receive and transmit arrays, the technique allows for re-use of the same frequencies in the multiple remote stations, with a resultant increase in system capacity or user density, e.g. the number of users per frequency per unit area (per cell or sector 5 thereof).

## 2.5 Concept of Separation of Signals in a "Waveguide":

Up to this point in the description, it has been tacitly assumed that the "incident signals" 27 shown in FIGS. 2A-2C and 3A-3C are signals transmitted 10 through space, the atmosphere, the ocean or some other relatively unbounded medium. As will be described in more detail in descriptions of various embodiments of the invention, cochannel signals transmitted on a waveguide of some type may also be received and processed in accordance with the principles of the invention. The term waveguide is used in quotation marks in the heading of this descriptive subsection 15 because the term is not intended to be limited to a waveguide operating at microwave frequencies, or to an optical waveguide in the form of an optical fiber or planar optical waveguide. Instead, the word waveguide as used in this specification is intended to cover any of various types of bounded transmission media, including microwave waveguides, optical waveguides, coaxial cables, or even twisted pairs of conductors 20 operating at relatively low frequencies.

A common attribute of these "waveguides" is that multiple signals may be transmitted along them using the same frequency but different modes of transmission, such as different polarization modes for microwave or optical waveguides, or, in the case of twisted-pair conductors, different signals being applied 25 to different wire-to-ground combinations. For various reasons, however, the propagation modes may become scrambled in the propagation medium and may become difficult or impossible to separate in a receiver. As shown in FIG. 6, a system in accordance with the invention can be usefully employed to separate such signals. Except for the sensor receiving system 20, the system of FIG. 6 is identical with the 30 FIG. 3A system for separating received signals. The "incident signals" 27 are received

from a signal "waveguide" 62, as defined in the preceding paragraph, and are sensed by "waveguide" sensors 52. In the case of a microwave or optical waveguide, the sensors 64 take the form of electromagnetic probes or optical sensors appropriately inserted into the waveguides. For twisted-pair conductors, the sensors may include 5 appropriate circuitry connected to the conductors and ground. Signals from the sensors 64 are subject to received signal conditioning, as indicated in block 66, and are then input to the signal separation system of the invention in the same way as signals from multiple elements of an antenna array. The system recovers the original signals as indicated on lines 38.

10 Another application of the invention is similar in some respects to the recovery of signals from a bounded waveguide. In magnetic recording systems using a high density recording medium in which recording tracks are positioned very close to each other, there is always the potential for crosstalk between the signals on adjacent parallel tracks. Maintaining an acceptably low level of crosstalk imposes a limitation on 15 the proximity of the tracks and the overall recording density. In this embodiment of the invention, a higher level of crosstalk can be tolerated because signals retrieved from adjacent tracks can be separated using the signal recovery system of the invention. In this case, the "waveguide" sensors 64 are adjacent playback sensors in a magnetic recording apparatus. There is no "waveguide" as such; nor are the signals transmitted 20 through an unbounded medium. Instead they are sensed electromagnetically from a recording medium on a moving magnetic tape or disk.

## 2.6 Preview of Iterative Embodiments to be Described:

As discussed in more general terms above, there are two alternative 25 iterative methods that may be used in accordance with the invention in the context of separation and recovery of cochannel signals. Before proceeding with the detailed descriptions of those methods in terms of specific embodiments, it may be helpful to provide a an overview of the iterative methods at a different level of abstraction from that of the preceding figures. FIG. 7 provides the basis for this overview. Some of the

technical terms used in FIG. 7 are introduced for the first time in this specification and may not be completely clear until the complete description is studied.

As shown in FIG. 7, the signal separation and recovery process involves a number of manipulations of the estimated generalized steering vectors (EGSVs) pertaining to the multiple signal sources. In block 70 EGSV initialization is performed. This is simply the selection of initial EGSV values (on line 30 in FIGS. 2A and 2B) from which to begin processing. It will be recalled that processing is performed in a batch mode in which sequential blocks of data are processed. The initial EGSVs may be estimates carried forward from an already processed previous block of data, or they may be generated from scratch, using either random quantities or a cumulant eigen-decomposition algorithm.

Another function performed in block 70 is to "project" the initial EGSVs into a  $P$ -dimensional signal space, where  $P$  is the number of signal sources. The antenna array provides sets of input data signals that are  $M$ -dimensional, where  $M$  is the number of elements in the array. Throughout the computations performed in accordance with the invention, there is often a design choice to be made because the mathematical manipulations may be performed on these  $M$ -dimensional vector quantities, or on corresponding  $P$ -dimensional quantities, where  $P$  is the number of signal sources. Ultimately, the recovered signals are output as  $P$  one-dimensional signals, since there is one recovered signal per source, but signal recovery requires beamforming in the sensor space. The transformation from  $M$ -dimensional sensor space to  $P$ -dimensional signal space is called "projection," and the reverse transformation, from  $P$ -dimensional signal space to  $M$ -dimensional sensor space, is called "backprojection."

Block 72 in FIG. 7 describes EGSV prioritization. This aspect of the invention has not yet been discussed but, simply stated, prioritization is needed to provide a rational basis for choosing which of multiple signals should be recovered first. The sensor array, having  $M$  elements, inherently limits the number of cochannel signals that may be recovered to  $M$ . If more than  $M$  signal sources are actively transmitting, the first  $M$  signals are selected on the basis of their non-Gaussianity, as

determined by either of two methods: using the C-matrix or beamforming and computing cross-cumulants. The resulting priority list of sources is passed to a signal separation iteration block 74, which uses one of the two iterative methods to obtain convergence for each EGSV in turn, starting with the highest priority source. The steps 5 of the iterative procedure include updating the EGSV using either the C-matrix or the beamforming and cross-cumulant computations, then using a conventional technique, such as the Gram-Schmidt procedure, to ensure that each EGSV is orthogonal to already-processed higher-priority EGSVs. These steps are repeated until convergence is achieved for each signal source.

10 Block 76 of FIG. 7 describes another practical issue in signal recovery systems that use batch processing. Each "port" from which a recovered signal is output in processing a block of data must be correctly associated with a recovered signal from the previous data block. This association is performed by comparing the EGSVs. The ports cannot be associated merely on their positions in the priority list because signal 15 sources may come and go from list as time passes.

Another batch processing issue is addressed in block 78 of FIG. 7. The phase angle of an EGSV generated in processing one block of data may not exactly match the phase angle as determined in the next block. This processing step applies an EGSV phase adjustment to eliminate any discontinuity from block to block.

20 Next, in block 80 of FIG. 6, the EGSVs are "backprojected" from the  $P$ -dimensional signal subspace to the  $M$ -dimensional sensor space and then, in block 82, the backprojected EGSVs are used to beamform and recover the output port signals.

This overview provides an introduction into the various embodiments 25 and forms that the invention may take. The foregoing and other aspects of the invention will now be discussed in more detail.

### 3.0 Preferred Embodiment Using eCURE:

As discussed more generally above, the present invention pertains to a 30 system and method for processing and recovering cochannel signals received at a

sensor array. In this descriptive section, a practical embodiment of the cumulant recovery (CURE) system is disclosed. Because this embodiment uses eigenvectors and eigenvalues in part of its computation, it is referred to as the eigenCURE system, or simply the eCURE system. The embodiment disclosed uses the first iterative method 5 (the beamform and cross-cumulant method, first introduced at 10 in FIG. 1). It will be understood, however, that the eCURE system may be modified to use the C-matrix iterative method (12, FIG. 1).

### 3.1 Overview And System Hardware:

10 FIG. 8A shows the basic components of the eCURE system, including a sensor array, indicated by reference numeral 110, which receives signals from various directions, as indicated at 112, a bank of receivers 114, and a sampler and analog-to-digital converter bank 116. The separate signals from the elements of the sensor array 110 are coupled directly to the receiver bank 114, which performs conventional 15 filtering and frequency downconversion functions. The sensor signals are then sampled at a high rate and converted to digital form in the sampler and analog-to-digital converter bank 16. At this point, the signals have been filtered, downconverted and digitized and processing is about to begin. It can be appreciated that, because each 20 sensor in the array 110 provides a stream of digitized signals, processing may be conveniently performed in batches or blocks of data. From time to time, reference will be made in this description to current and previous data blocks. The block size is critical only in the sense that the size selected affects processing speed and accuracy of estimation.

25 The first major processing step is preprocessing the sensor data, which is performed in a preprocessing computer 120. As will be discussed in more detail with reference to FIG. 10, the preprocessing computer 120 performs four important functions:

- It "whitens" the directional components of the signals using a technique known as eigendecomposition, which will be discussed further below.

- It estimates the number of signal sources being received.  $P$  is the number of sources and  $P_e$  is the estimated number of sources.
- It reduces the dimensionality of the sensor data from  $M$ , the number of sensors, to  $P_e$ , the estimated number signal sources.
- 5       • It scales the numerical values of the signals to normalize the powers of the sources, permitting weak signals to be separated in addition to stronger ones.

The other major components of the cochannel signal recovery system are a signal recovery controller 122, multiple signal extraction ports 124.1 through 124.L, 10 an orthogonalizer 126, and multiple demodulators 128. Preprocessed sensor signals are transmitted over lines 130 in parallel to each signal extraction ports 124.1. Each port in this embodiment of the invention is implemented as a separate computer processor. Using the iterative technique described above with reference to FIGS. 2A and 3A, each of the signal extraction ports 124 generates output signals derived from a 15 separate source. These signals are output on lines 132 to the demodulators 128, which produce usable output signals on lines 134. If the information contained in the signals is audio information, the outputs on lines 134 may be connected to separate loudspeakers or other audio processing equipment (not shown). The function of the orthogonalizer 126 is to ensure that each of the ports 124 is associate with a separate 20 signal source. The signal recovery controller 122 performs various control functions in conjunction with the signal extraction ports 124 and the orthogonalizer 126. The controller 122 receives the source count estimate  $P_e$  from the preprocessing computer 120 over line 136 and also receives eigenstructure parameters from the preprocessing computer over line 138. The latter are also transmitted to the signal extraction ports 25 124, and the source count estimate is transmitted to the orthogonalizer 126. The controller 122 also sends a priority list to the orthogonalizer 126 over line 140. Finally, the controller 122 sends adaptation flags to the signal extraction ports 124 over lines 142 and receives capture strength values from the signal extraction ports over lines 144. The specific functions of these signals will become apparent as the

description proceeds. Basically, one function of the controller 122 is to keep track of signal sources as they appear and disappear and to make sure that the signal extraction ports 24 and the orthogonalizer 126 handle appearing and disappearing signal sources in an appropriate manner.

5 In the general terms used in FIG. 3A, the sensor receiving system 20 includes the sensor array 110, the receiving bank 114, the sampler and analog-to-digital converter 116 and the preprocessing computer 120. The functions performed by the linear combiners 26, the EGSV computation modules 22 and the supplemental computation module for signal recovery 24A, are performed in the signal recovery 10 controller 122, the signal extraction ports 124 and the orthogonalizer 126. Because this practical embodiment must maintain association of signal sources to physical output ports, and must be able to adapt dynamically to the appearance and disappearance of signal sources, the architecture of the system is necessarily different from the conceptual architecture of FIGS. 2A, 3A and 4A. The fundamental functions 15 performed in the system of FIG. 8A are, however, the same as those described with reference to the earlier figures.

FIG. 8B is a hardware block diagram of one implementation of the eCURE system of the present invention, as used to separate multiple signals containing audio information. Identical reference numbers have been used in this figure to refer 20 to components that appear in both FIG. 8A and FIG. 8B. The preprocessor computer 120 is implemented as a separate circuit card. It is of little significance whether the preprocessor computer is implemented on a single circuit card or in a stand-alone computer. The functions performed in both cases would be identical. Similarly, the controller 122 and orthogonalizer 126 are implemented in one computer on a single 25 circuit card, as indicated in FIG. 8B. The signal extraction ports 124, one of which is shown, are implemented on separate computers on circuit cards and the demodulators 128 are also implemented on a separate computer. All of the computers mentioned above may be of any appropriate type, but in a presently preferred demonstration embodiment, they are Intel model i860 processors. The computers are connected to a

high-speed crossbar switching network 150, such as Part No. ILK-4, from Mercury Computer Systems, Lowell, MA, 01854.

The sensors 110 may be of any appropriate type, such as Part No. 10-183-244, from TRW Inc., Sunnyvale, CA, 94088. The receivers 114 in this embodiment include a VME synthesizer module (Part No. 1600M SYN-5, from APCOM Inc., Gaithersburg, MD, 20878), a local oscillator module (Part No. 1600M LOD-1, also from APCOM Inc.) and a VME RF converter module (Part No. 1600M RFC-5, also from APCOM Inc.). The digitizer bank 116 may include an Access256 motherboard (Part No. MOB256-4) and analog input and digital output cards from 10 Celerity Systems, Inc., San Jose, CA, 95117.

The receiver bank 114 tunes each sensor to the desired frequency and downconverts any signals received. One receiver is allocated to each sensor. The receivers 114 enable the system to isolate a single frequency of interest and to translate it to a frequency where it can be more conveniently digitized and processed. No 15 demodulation is performed at this point. For example, one embodiment of the invention has receivers that downconvert the received signals to a center frequency of 225 kHz and a bandwidth of 100 kHz (specifically the 3 dB bandwidth).

The digitizer bank 116 converts the received signals to digital samples. Only real samples, not complex samples, are generated at this stage. In the illustrative 20 system, the digitizer bank 116 consists of a digitizer motherboard and an input daughtercard that samples up to eight channels simultaneously at a rate of up to 10 megasamples per second. The samples are exported for further processing through an input card 151. The data processing system performs digital filtering of the input data, with the digital filtering card 152, and converts the real samples to complex values 25 needed for processing, using a real-to-complex conversion card 153.

All of the processor cards mentioned above are connected to the high-speed crossbar switching network 150. A system manager 154 in the form of a Model 68040 CPU (Part No. CPU-40B/16-02, from Force Computers Inc., San Jose, CA, 95124) controls this demonstration system, with operator interface being provided by a 30 workstation 56, such as a Powerlite notebook workstation (Part No. 1024-520-32, from

RDI Computer Corporation, San Diego, CA, 92008). In this hardware architecture, the demodulated signal outputs are connected to loudspeakers 157 and a hard disk drive 158 is provided for storage of received messages. The system manager tunes the receivers 116, instructs the digitizer to record samples, configures and initiates 5 operation of the data processing system, and controls a peripheral interface board (Part No. MVME 162-63, from Motorola Computer Group, Tempe, AZ, 85282), through which communication is had with the loudspeakers and the hard disk. It must be understood that, because this is a demonstration system, many of these components would not be needed in some implementations of the invention. As noted earlier, many 10 of the components could be conveniently implemented in the form of a single integrated circuit chip, or multiple chips.

FIG. 9, which is broken into two figures designated FIGS. 9A and 9B, is a block diagram similar to FIG. 8A but showing in each block more detail of the functions performed by each component of the system. The functions will be described 15 with reference to the more detailed diagrams that follow. Another feature shown in FIG. 9 but not in FIG. 8A is the output of generalized steering vectors on lines 170. The generalized steering vectors, as discussed earlier in this specification, are an important product of the signal recovery process, along with the recovered signal outputs. The generalized steering vectors are shown as being used in a DF search 20 processor 172, which generates signal source bearings or directions of arrival (DOA), output on lines 174, consistent with the description with reference to FIG. 4B.

### 3.2 Preprocessing:

The functions performed by the preprocessing computer 120 are shown 25 in detail in FIG. 10. The preprocessor performs a block-by-block analysis of "snapshots" of data from the sensor array, which has  $M$  elements. The preprocessor determines the eigenvectors, the number of signal sources  $P$ , and the signal subspace of the received array measurement data. The preprocessor also filters the received array data, transforming it from  $M$ -dimensional sensor space to  $P$ -dimensional signal 30 subspace. This transformation also renders the steering vectors of the transformed

sources orthogonal to each other, which greatly accelerates convergence on recovered signal solutions later in the processing, and the transformed source powers are made equal.

5 A received signal that satisfies the narrow-band assumption (to be defined below) can be described by the following equation:

$$\mathbf{r}(t) = \mathbf{As}(t) + \mathbf{n}(t),$$

where  $\mathbf{r}(t)$  denotes the array measurements collected by  $M$  sensors,  $\mathbf{n}(t)$  is the measurement noise,  $\mathbf{A}$  is the steering matrix that models the responses of the sensors to the directional sources, and  $\mathbf{s}(t)$  is a time-varying signal. The sampled sensor signals, 10 represented by a function of time  $\mathbf{r}(t)$ , are input to the preprocessing computer until a complete block of data has been received. While the block is being further processed, another block of data is input to a buffer in the computer (not shown). As indicated at 180, each block of data is first subject to computation of an array covariance matrix for the current block of data. The sample covariance matrix  $\hat{\mathbf{R}}$  from  $N$  samples or 15 "snapshots" of data is given by:

$$\hat{\mathbf{R}} = \frac{1}{N} \sum_{t=1}^N \mathbf{r}(t) \mathbf{r}^H(t) .$$

As indicated at 182, a further important step in preprocessing is eigendecomposition, which decomposes the covariance matrix as:

$$\hat{\mathbf{R}} = \mathbf{E} \Lambda \mathbf{E}^H, \mathbf{E}^H \mathbf{E} = \mathbf{I}_M,$$

20 where the diagonal matrix  $\Lambda = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_M)$  contains the eigenvalues of  $\hat{\mathbf{R}}$  (which are positive) in a descending order, and the columns of the matrix  $\mathbf{E}$  consists of the corresponding eigenvectors. In this description, the subscript appended to the identity matrix  $\mathbf{I}$  indicates its size. In the case of true statistics and with fewer sources than sensors ( $P < M$ ), the last  $(M-P)$ , eigenvalues are identical and they are equal to the 25 noise variance  $\lambda_{M-P+1} = \dots = \lambda_M = \sigma^2$ . With sample statistics, the last  $(M-P)$  eigenvalues are different with a probability of one, and a statistical test has to be performed to determine the number of sources  $P$ .

In the presently preferred embodiment of the invention, the preprocessing computer uses a combination of two estimates of the number of sources, as indicated in block 184: the estimate determined by Akaike's Information Criteria (AIC) and the estimate determined by Rissanen's Minimum Description Length (MDL) principle. Specifically, the preprocessing computer averages the AIC and MDL functions and finds the single maximizer of the average. The equations for making this estimation are given, for example, in a dissertation by Mati Wax submitted to Stanford University in March 1985, and entitled "Detection and Estimation of Superimposed Signals," and in particular the subsection headed "Estimating the Number of Signals," beginning on page 69 of the paper. AIC generally overestimates the number of sources, and MDL generally underestimates the number of sources. By averaging the two estimates, a good result is obtained. The averaged estimate of the number of sources is given as the minimizer of the cost function:

$$P_e = \operatorname{argmin}_{0 \leq k < M} \left\{ N \log \left[ \left( \frac{1}{M-k} \sum_{i=k+1}^M \lambda_{i,i} \right)^{M-k} \middle/ \prod_{i=k+1}^M \lambda_{i,i} \right] + \frac{1}{2} k(2M-k) \left( 1 + \frac{1}{2} \log(N) \right) \right\}.$$

15 After the number of sources is estimated, the preprocessor computer computes estimates of the eigenvectors and eigenvalues of the signal and noise subspaces:

$$\mathbf{E} = [\mathbf{E}_s, \mathbf{E}_n], \quad \Lambda = [\Lambda_s, \hat{\sigma}^2 \mathbf{I}_{M-P_e}], \quad \hat{\sigma}^2 = \frac{1}{M-P_e} \sum_{k=P_e+1}^M \lambda_k.$$

$\mathbf{E}_s$  and  $\mathbf{E}_n$  are estimates of signal and noise subspace eigenvectors, respectively, and  $\hat{\sigma}^2$  is an estimate of the noise power. The diagonal matrix  $\Lambda_s$  contains the estimates of 20 signal subspace eigenvalues. Once the subspaces are found, the preprocessor computer determines the transformation matrix  $\mathbf{T}$ , as indicated in block 186, from:

$$\mathbf{T} = \mathbf{E}_s (\Lambda_s - \hat{\sigma}^2 \mathbf{I})^{-1/2}.$$

The transformation  $\mathbf{T}$  is then applied to the sampled measurements  $\mathbf{r}(t)$ , as indicated in block 188:

$$25 \quad \mathbf{y}(t) = \mathbf{T}^H \mathbf{r}(t) = \mathbf{T}^H \mathbf{A} \mathbf{s}(t) + \mathbf{T}^H \mathbf{n}(t) = \mathbf{y}_s(t) + \mathbf{T}^H \mathbf{n}(t),$$

where  $\mathbf{y}_s(t)$  denotes the signal component in  $\mathbf{y}(t)$ . It can be proved that the covariance matrix of  $\mathbf{y}_s(t)$  is the identity matrix. This indicates that the steering vectors of the

sources after transformation to the  $P_e$ -dimensional subspace are orthogonal to each other and the source powers are equalized.

The transformation reduces the dimensionality of the sensor measurements from  $M$ , the number of sensors, to  $P_e$ , the estimated number of signal sources. The eigendecomposition performed in the preprocessing computer is a well known technique, sometimes referred to as spatial prewhitening, originally developed for use in passive sonar signal processing. It is described in more detail in a number of texts on signal processing. For example, see "Detection of Signals in Noise," by Anthony D. Whalen, Academic Press, New York (1971), beginning at page 392. In spatial prewhitening, noise components at each sensor are assumed to correlated (i.e., not completely random noise). The prewhitening process operates on the noise signals to render them uncorrelated (i.e., "whitened"). An alternative to eigendecomposition is to use covariance inversion in preprocessing. In effect, the latter process whitens both noise and signal components of the sensor signals and it can be at least intuitively understood that this is a less desirable approach since it renders the signals less easy to separate from the noise than if spatial prewhitening of the signal only were used. However, the present invention will still separate cochannel signals using covariance inversion instead of eigendecomposition as a preprocessing step. Currently, eigendecomposition, or spatial prewhitening, is the preferred approach for preprocessing.

### 3.3 Operation of an Active Signal Extraction Port:

A single active signal extraction port, one of the  $L$  ports 124 shown in FIG. 8A, is shown in detail in FIG. 11, which extends over two sheets, as FIGS. 11A and 11B.  $L$  is the number of physical ports allocated for signal extraction and is less than  $M$ , the number of sensors. For generality, the illustrated port is referred to as the  $k$ th port 124.k, and signals pertaining specifically to this port are referred to by signal names that include the prefix  $k$ . An "active" port is one that has been assigned responsibility for separating a signal from the received signal data. The functions performed in an active port are critical to the invention and are illustrated in FIG. 11.

The active signal extraction port 124.k receives as inputs over line 130 the preprocessed sensor data  $\mathbf{y}(t)$ . As in the preprocessing computer 120 (FIG. 7), the sensor signals are described as being processed in blocks, although it will be understood that an alternative embodiment of the invention could be devised to process 5 the signals continuously. The principal output from the port is a recovered signal, designated  $g_k(t)$ . An important intermediate output is a vector quantity called the normalized cumulant vector, referred to as  $\mathbf{b}_k$ . Another important output is the generalized steering vector  $\mathbf{a}_k$ , which defines the directional location of the signal source.

10 To highlight the (block) iterative nature of the algorithm, the quantities related to the  $m$ th analysis block are identified in this descriptive section by using the additional index  $m$ . For example, the steering vector estimate provided by the  $k$ th port after the  $m$ th block is processed is denoted as  $\mathbf{a}_k(m)$ . The time variable  $t$  spans from the start of the  $m$ th block to the end of the  $m$ th block, and, with  $N$  snapshots per block, can 15 be expressed at  $t \in [(m-1)N + 1, mN]$ . The quantities  $\mathbf{E}$ ,  $\Lambda$  and  $\mathbf{T}$  are obviously obtained by processing the  $m$ th block of data, so, for simplicity, they are not written with the  $(m)$  index.

It is both logical and convenient to begin describing operation of the signal extraction port at the point in time when the port has just been made active. No 20 accurate signal has been recovered and no cumulant vector has been computed since the port became active. The block number being of input data is examined, as indicated at 200, to determine whether the current block is the first block. If so, the steering vector  $\mathbf{a}_k(0)$  is set to an initial random vector with a unit norm. As shown in processing block 102, the steering vector  $\mathbf{a}_k(m-1)$  is first projected to the signal subspace by transforming 25 it into a value  $\mathbf{v}_k$ , using the transformation  $\mathbf{T}$ , which is input to block 202 as shown. The steering vector projected into the signal subspace is computed as:

$$\mathbf{v}_k = \mathbf{T}^H \mathbf{a}_k(m-1).$$

These computed values are passed to a beamformer 204, which recovers an auxiliary waveform using  $\mathbf{v}_k$  as weights:

$$u_k(t) = v_k'' y(t) / \| v_k \|.$$

The scaling by the norm of  $v_k$  is performed to ensure numerical stability in the cumulant computations. At convergence, the norm of  $v_k$  should be unity (because of the preprocessing performed on the measurements). The auxiliary source waveform is provided to the cumulant vector computer 206, which computes sample estimates of the cross-cumulant vector  $b_k$ , which has components defined by:

$$(b_k)_i = \text{cum}(u_k(t), u_k^*(t), u_k^*(t), y_i(t)), \quad 1 \leq i \leq P_e,$$

where  $(b_k)_i$  denotes the  $i$ th component of  $b_k$ . The asterisk indicates that the conjugate of the process  $u_k(t)$  is used in two of the four quantities of which the cumulant is computed. The cumulant vector computer computes a fourth-order cumulant vector of the input signals. More specifically, the vector is the cumulant of four quantities derived from the input signals. An introduction to cumulants and their properties is provided in Section 20.4 to this specification.

After the cumulant vector  $b_k$  has been computed in the cumulant vector computer 106, the capture strength  $c_k$  is computed in a capture strength computer 208.

The capture strength computer 208 determines the convergence condition of a port by evaluating the degree of non-Gaussianity of the auxiliary signal  $u_k(t)$ , and the amount of change between  $b_k$  and  $v_k$ . At convergence, these two vectors should be pointing at the same direction. The non-Gaussianity of the auxiliary signal can be determined from the ratio of its fourth-order cumulant to its squared power:

$$\xi_k = \frac{|\text{cum}(u_k(t), u_k^*(t), u_k^*(t), u_k(t))|}{(E\{u_k(t)u_k^*(t)\})^2}$$

Using cumulant properties, we obtain

$$\xi_k = \frac{|\text{cum}(u_k(t), u_k^*(t), u_k^*(t), v_k'' y(t) / \| v_k \|)|}{(E\{u_k(t)u_k^*(t)\})^2} = \frac{|\mathbf{v}_k'' \mathbf{b}_k| / \| v_k \|}{(E\{u_k(t)u_k^*(t)\})^2}$$

The denominator can be computed from the auxiliary signal  $u_k(t)$ . Since the covariance matrix of the signal component of  $y(t)$  is the identity matrix, the denominator can be ignored when the signal to noise ratios (SNRs) are high enough. The similarity between  $b_k$  and  $v_k$  can be computed from the following:

$$\eta_k = \frac{|\mathbf{v}_k^H \mathbf{b}_k|}{\|\mathbf{v}_k\| \|\mathbf{b}_k\|}.$$

The capture strength  $c_k$  can be determined from  $\xi_k$  and  $\eta_k$ . One way is to let  $c_k = \xi_k \cdot \eta_k$ . Alternatively, we can set  $c_k = \xi_k$  or  $c_k = \eta_k$ .

5 The capture strengths  $c_k$  are provided to the controller unit for priority determination. The cross-cumulant vector is normalized by its norm and fed to the orthogonalizer:

$$(\mathbf{b}_k(m) = \mathbf{b}_k / \|\mathbf{b}_k\|).$$

If the active ports capture different sources, their cross-cumulant vectors should be orthogonal. To force the active ports to capture different sources, the 10 orthogonalization unit uses the Gram-Schmidt procedure and outputs orthogonalized cumulant vectors (d vectors) to the ports. The steering vectors are determined from the orthogonalized cumulant vectors according to

$$\mathbf{a}_k(m) = \mathbf{E}_s (\Lambda_s - \hat{\sigma}^2 \mathbf{I}_{P_s})^{1/2} \mathbf{d}_k(m) = \mathbf{T}(\Lambda_s - \hat{\sigma}^2 \mathbf{I}_{P_s}) \mathbf{d}_k(m).$$

The steering vectors are provided to the controller unit in order to 15 determine the port that loses its signal in the event of a source drop-out or to determine which port will be activated in the case of a new signal. The steering vectors can also be used by an optional DF search unit to determine the source bearings.

Finally, the active port determines the signal waveform from the source it is tracking. However, it is necessary for an active port to maintain gain and phase 20 continuity of its recovered signal at block transitions in order to prevent block-to-block gain and phase modulation of the recovered signal. To accomplish this goal, we need to examine the properties of the algorithm in more detail. The algorithm normalizes the source waveforms to have unit variance and estimates the steering vectors based on this normalization, i.e., eCURE views the measurements as:

$$25 \quad \mathbf{r}(t) = (\mathbf{A} \Sigma_{ss}^{1/2} \mathbf{D})(\mathbf{D}^* \Sigma_{ss}^{-1/2} \mathbf{s}(t)) + \mathbf{n}(t),$$

where  $\Sigma_{ss}$  is the covariance matrix of the directional sources which is diagonal since the sources are independent ( $\Sigma_{ss} = E\{\mathbf{s}(t)\mathbf{s}(t)^H\}$ ). The diagonal matrix  $\mathbf{D}$  contains arbitrary phase factors associated with the blindness of the steering vector estimation procedure.

Even when the sources are stationary, there can be gain (due to  $\Sigma_s$ ) and phase modulations (due to  $\mathbf{D}$ ) on the steering vectors estimates and waveform estimates.

There are two different ways to determine gain and phase modulations for each block. We can compare the steering vector estimates  $\mathbf{a}_k(m)$  and  $\mathbf{a}_k(m-1)$ ,  
 5 which should be pointing to the identical direction at convergence. Suppose, due to power changes and arbitrary phase rotations, the following relationship holds between the steering vectors:

$$\mathbf{a}_k(m) \equiv q_k \mathbf{a}_k(m-1)$$

where  $q_k$  accounts for the gain and phase factor between the two steering vector  
 10 estimates. We can estimate  $q_k$  using least-squares:

$$\hat{q}_k = \mathbf{a}_k^H(m-1) \mathbf{a}_k(m) / \|\mathbf{a}_k(m-1)\|^2$$

Using

$$\mathbf{a}_k(m) = \mathbf{E}_s (\Lambda_s - \hat{\sigma}^2 \mathbf{I})^{1/2} \mathbf{d}_k(m)$$

and

$$\mathbf{a}_k(m-1) = \mathbf{E}_s (\Lambda_s - \hat{\sigma}^2 \mathbf{I})^{1/2} \mathbf{v}_k$$

15 we obtain an alternative way to compute  $q_k$ :

$$\hat{q}_k = \mathbf{v}_k^H (\Lambda_s - \hat{\sigma}^2 \mathbf{I}) \mathbf{d}_k(m) / (\mathbf{v}_k^H (\Lambda_s - \hat{\sigma}^2 \mathbf{I}) \mathbf{v}_k).$$

In the  $m$ th block, the  $k$ th block scales the steering vector estimate by  $q_k$ ,  
 relative to the previous block. Therefore, it scales the waveform estimate at the  $m$ th  
 20 block by the reciprocal of this quantity. Hence we need to multiply the waveform  
 estimate by  $q_k$  (or by its estimate) in order to undo the scaling done by the processor,  
 which is described as below:

$$g_k(t) = \hat{q}_k (\mathbf{d}_k^H \mathbf{y}(t)) = (\hat{q}_k^* \mathbf{d}_k)^H \mathbf{y}(t) = \mathbf{w}_k^H \mathbf{y}(t)$$

The second way to compute  $q_k$  is to force the first component of the steering vector  
 25 estimate to be unity. In this process, we simply let  $q_k$  be the first component of  $\mathbf{a}_k(m)$ .  
 After  $q_k$  is determined,  $\mathbf{w}_k$  will be determined using the orthogonalized cumulant vector  
 $\mathbf{d}_k(m)$  and  $q_k$ .

Once a source waveform is recovered, it is available for subsequent processing as desired. It can be recorded or demodulated and listened to with headphones or loudspeakers.

5 3.4 The Signal Recovery Controller:

Now that the basic signal extraction method has been described and before proceeding to a description of the orthogonalizer function, it is logical to consider next how the signal recovery controller 122 (FIG. 8A) operates because this 10 affects operation of the orthogonalizer 126 and the signal extraction ports 124. As briefly discussed with reference to FIG. 9, an important function of the controller 122 is to detect changes in the status (ON or OFF) of signal sources and to identify lost sources. In addition, the controller 122 maintains a priority list of ports and a related set of adaptation flags that indicate which ports are active.

As shown in FIG. 13, which is spread over three pages as FIGS. 13A, 15 13B and 13C, the functions of the controller 122 include logic to detect changes in the number of signal sources, indicated by block 220, port allocation logic 222, priority list determination logic 224, and adaptation flag logic 226. The logic 220 to detect changes in the number of sources assumes that there is no more than one change in the number of sources from one data block to the next. The logic receives the estimated 20 number of signals  $P_e$  from preprocessing computer 120 and compares the  $P_e$  of the previous block with the  $P_e$  of the current block. The results of the comparison determine the value of source change flag, referred to simply as "Flag." Flag is set to zero for the initial block. There are three possible outcomes of the comparison for subsequent blocks of data:

25

1. If current  $P_e$  = previous  $P_e$ , Flag = 0
2. If current  $P_e$  > previous  $P_e$ , Flag = 1 (new source ON)
3. If current  $P_e$  < previous  $P_e$ , Flag = 2 (source OFF).

The Flag value is transmitted over line 228 to the port allocation logic 222, which is called into operation only if Flag=2, indicating that a source has been

lost. The function of the port allocation logic 222 is to determine which of the active ports 124 was last processing signals from the source that has just been lost. The basic principle employed to make this determination is to identify which port has a steering vector with the greatest component in the current noise subspace. Each signal that 5 contributes to the measurements has a steering vector that is orthogonal to the current noise subspace determined from the sample covariance matrix  $\hat{R}$ . (In a simple three-dimensional space, one could think of a first signal eigenvector aligned with the x-axis direction and a second signal eigenvector aligned with the y-axis direction. The signal subspace for the two active signals includes the x-axis and y-axis directions. The noise 10 subspace is the space defined by all remaining axes in the space. In this case, the noise subspace eigenvector is in the z-axis direction.)

When a signal disappears and drops out of consideration, the current noise subspace then includes the space previously occupied by the signal. In the three-dimensional example, if the x-axis signal disappears, leaving only the y-axis signal, the 15 noise subspace is redefined to include a plane in the x and z directions. To recognize which signal was lost, the port allocation unit uses the steering vector estimates from the previous data block (indicative of the active sources before one was lost), and projects these vectors into the noise subspace as defined for the current data block. The steering vector from the previous data block that lies completely in the current data 20 block noise subspace, or the one that has the largest component in the noise subspace, is determined to be the signal that was lost between the previous and current data blocks. Again, using the three-dimensional example, if x-axis signal disappears and the new noise subspace is redefined be the x-z plane, then projection of the previous x and y signals into the current noise subspace results in a finding that the x-axis signal, 25 lying wholly in the current noise subspace, is the signal that was lost.

More specifically, the logic 222 obtains the steering vector estimates from all of the ports that were active in the previous data block, and normalizes them (i.e., scales them have a unit norm). Steering vector estimates are obtained for only the first  $(P_e + 1)$  ports in order of decreasing capture strength. The port allocation

logic is concerned with the direction of the steering vectors in space and any differences in magnitude arising from different signal strengths should be eliminated. Then the normalized steering vectors are projected onto the current noise subspace, as provided from the preprocessing computer 120 in the form of noise subspace 5 eigenvectors  $E_n$ . For example, if  $a_k(m-1)$  is a steering vector estimate from the  $k$ th port that was active in the previous block, then the port allocation logic 222 computes the "leakage" of the steering vector of the  $k$ th port into the current noise subspace from:

$$||E_n E_n^H a_k(m-1) / ||a_k(m-1)|| ||.$$

10 The logic then declares the port that has the greatest leakage into the noise space to be inactive by setting its adaptation flag to zero. Also the port's capture strength is set to a value MIN, which is a system parameter set to some very low value, such as 0.001. It will be recalled that the capture strength is computed in each active port as described earlier. However, the controller 222 can overwrite the previously computed value 15 when it is determined that a port has become inactive.

For example, suppose that five ports are available for use, with three sources present in the previous data block. Port 1 was locked onto Source 3, Port 3 was locked onto Source 1, and Port 5 was locked onto Source 2. Assume further that Source 3 turned off just before the current block and that the following capture 20 strengths were determined for the previous and current data blocks:

Port No.	Previous Source No.	Previous Capture Strength	Current Source No.	Current Capture Strength
1	3	0.99	-	0.001
2	-	0.001	-	0.001
3	1	0.995	1	0.995
4	-	0.001	-	0.001
5	2	0.98	2	0.98

In the previous data block, Port 2 and Port 4 were inactive and had their capture strengths set to 0.001. When Source 3 turned off, the port allocation logic 222 determined that Port 1 had lost its signal, using the analysis discussed above.

Inherent in the list of capture strengths is a priority list of ports (i.e., a list of port numbers in order of decreasing capture strength). Therefore, the priority list based on the previous data block is [3,1,5,2,4] and the priority list based on the current data block is [3,5,1,2,4]. The convention adopted is that, when ports have identical capture strengths, they are assigned priorities based on port numbers. The priority list determination logic 224 generates the priority list in this manner, based on 10 the capture strength list transferred from the port allocation logic 222. The priority list is used by the adaptation flags logic 226 to generate a list or vector of adaptation flags. The adaptation vector contains  $L$  elements, where  $L$  is the number of physical ports in the system. In the example given above, the adaptation flags vector for the previous data block is [1,0,1,0,1] and for the current data block is [0,0,1,0,1]. The adaptation 15 flags vector is supplied to multiple port signal recovery unit (124, 126, FIG. 9), and specifically to the signal extraction ports 124. The priority list is also supplied to the multiple port signal recovery unit, and specifically to the orthogonalizer 126, which will be discussed in the next descriptive section.

The purpose of the priority list is to facilitate an orderly allocation of 20 signal sources to ports, from the lowest port number to the highest. Further, when a signal source turns on, it is desirable that the most recently freed port be made available for assignment to the new signal, to provide continuity when a source turns off and on again without a change in the status of other sources.

If there is a new source (i.e., Flag=1), then this unit first obtains the 25 previous block steering vector estimates from the ports that are inactive in the previous block (Ports  $P_e$  to  $L$  in the priority list), and normalizes them to have unit norm. It then projects these steering vectors onto the current noise subspace. For example, if  $a_k(m-1)$  is a steering vector estimate from a port that was inactive in the previous block, then the Port Allocation Unit computes the port's leakage from (here  $\|a_k(m-1)\|$  30 denotes the norm of vector  $a_k(m-1)$ ):

$$\left\| \mathbf{E}_n \mathbf{E}_n^H \mathbf{a}_k(m-1) / \|\mathbf{a}_k(m-1)\| \right\|,$$

and declares the port which has the *minimum leakage* as active (sets its adaptation flag to one) and overwrites the port's capture strength with  $2 \times \text{MIN}$ , where  $\text{MIN}$  is a system parameter that is nominally set to 0.001. This is done to make the newly 5 activated port be the last in the priority list. (The capture strength of a port is computed by the multiple port signal recovery unit described earlier in this specification. The controller, however, can overwrite the computed value as described above.)

### 10 3.5 The Orthogonalizer:

As already briefly discussed, the orthogonalizer 126 functions to ensure that each port is consistently assigned to process only one signal source, which is to say that each active port captures a different source. The orthogonalizer 126 receives a normalized cumulant vector from each active port, the vector being represented by  $\mathbf{b}_k$  15 for the  $k$ th port. The orthogonalizer 126 outputs back to each port an orthogonalized cumulant vector, which is  $\mathbf{d}_k$  for the  $k$ th port. The orthogonalizer also receives the priority list from the signal recovery controller 122, so has knowledge of the identities of the active ports and their respective associated capture strengths, and also receives the estimated number of signals  $P_e$ , from the preprocessing computer 120.

20 The orthogonalizer forces the active ports to capture different sources by orthogonalizing their cumulant vectors, which, in turn, are estimates of the steering vectors in the dimensionally reduced space. (It will be recalled that, in the preprocessing computer 120, the dimensionality of the data is reduced from  $M$ , the number of sensor elements, to  $P_e$ , the estimated number of sources.) Ideally, the 25 cumulant vectors for active ports should be orthogonal to each other, to cause the ports to capture different source signals and to prevent two ports from locking up on the same source signal. From the priority list and the estimated number of signals  $P_e$ , the orthogonalizer forms a  $P_e$  by  $P_e$  matrix  $\mathbf{Z}$  from the active port steering vectors  $\mathbf{b}_k$  such that the  $k$ th column of the matrix  $\mathbf{Z}$  is the steering vector of the port that is the  $k$ th item

in the priority list. The orthogonalizer uses a known procedure known as the classical Gram-Schmidt (CGS) algorithm to perform the orthogonalization operation. The Gram-Schmidt algorithm is described in a number of texts on matrix computations, such as *Matrix Computations*, by Gene H. Golub and Charles F. Van Loan (The Johns Hopkins University Press, 1983), pp. 150-154.

As applied to the present system, the Gram-Schmidt algorithm is applied to the matrix  $Z$  to obtain a decomposition of the type:

$$Z = QR,$$

where  $Q$  is an orthogonal matrix ( $Q^T Q = I$ ), and  $R$  is an upper triangular matrix.

10 Although the Gram-Schmidt orthogonalization procedure is used because of its simplicity, there are alternatives that might also be used in the invention, such as QR-decomposition and the Modified Gram-Schmidt (MGS) procedure. After the orthogonal matrix  $Q$  is determined, its columns are shipped back to the ports as orthogonalized cumulant vectors  $d_k$ . Specifically, the  $k$ th column of the  $Q$  matrix is sent back as  $d_k$  to the port that is the  $k$ th entry in the priority list. Regardless of the method used, the effect of the orthogonalizer is to produce a set of  $P_e$  cumulant vectors that are orthogonal to each other.

### 3.6 Operation at an Inactive Port:

20 When a port is determined to be inactive, as indicated by a zero adaptation flag, the port performs three simple functions, as shown in FIG. 14. First, its output signal  $g_k(t)$  is set to zero. Second, its capture strength  $c_k$  is set to a minimum value MIN. Finally, the last steering vector  $a_k$ , estimated in the port just before it became inactive, is stored in a memory device associated with the port, to facilitate 25 recapture of the same signal that was lost, if it should turn on again in the near future. More specifically, the adaptation flag input to the inactive port is delayed by one data block time. Then, using the delayed adaptation flag, the port stores a steering vector either from two blocks earlier, if the delayed flag has a value of 1, or one block earlier, if the delayed flag has a value of zero.

#### 4.0 Alternate Embodiment Using Covariance Inversion Cure (CiCURE):

The basic cumulant recovery (CURE) system described in Section 3.0 uses eigendecomposition in preprocessing and is referred to as eigenCURE (eCURE) 5 for convenience. Another variant of the CURE system uses covariance inversion instead of eigendecomposition and is referred to as covariance-inversion CURE (CiCURE). CiCURE is best thought of as a low-cost approximation to the high-performance eCURE system. As such, it shares most of the same advantages over standard CURE as the eCURE method.

10 Certain conditions must be met in order for CiCURE to mimic eCURE and realize the same advantages. The conditions are:

- Sensor noises must be additive Gaussian noise (eCURE assumes independent, identically distributed, additive Gaussian noise).
- Received signal powers must be much greater than the noise.
- 15 • Sample covariance matrix and its inverse used by CiCURE must be accurate enough to prevent leakage into noise subspace.

Under stationary or steady-state signal conditions, this implies a need for a sufficiently long processing block size. Under these conditions, the prewhitening transformation used in CiCURE is a good approximation to that used in eCURE, and 20 the two systems have similar performance properties. This section of the specification describes the components of a signal separation/recovery system that is based on the CiCURE algorithm.

The CiCURE signal separation/recovery system incorporates a spatial prewhitening transformation based on the inverse of the input sample covariance matrix 25 (this operation is performed by using an eigendecomposition in the eCURE). The received signal data is filtered or transformed by the prewhitening operation in the CiCURE, unlike eCURE. The prewhitening done in the CiCURE is implicit in the mathematics of the signal recovery ports, and it is only necessary to compute a matrix decomposition of the input sample covariance matrix. This latter operation is done in a 30 preprocessor, whose output is made available to all of the signal recovery ports. Key

characteristics of the implementation described below are that the iterative convergence of the CURE algorithm is realized over several blocks instead of within a single block, and "high-priority" ports converge sooner than "low-priority" ports.

5 A signal recovery system based on the CiCURE method is simpler than one based on the eCURE. There are two main architectural components to the method: a preprocessor unit which computes a matrix decomposition and a set of signal recovery ports hierarchically arranged.

In addition, there can be two optional units: demodulators, to complete the recovery of the separated signal for the purpose of recording or listening, and a 10 direction-finding (DF) search unit to provide copy-aided DF.

A block diagram for an overall signal recovery system based on the CiCURE method is shown in FIG. 15. The details of the preprocessor 120' and the signal recovery ports (124.1, 124.2, etc.) that are unique to the CiCURE method are described below. All other system details are as previously described for the eCURE 15 system.

The preprocessor 20' computes a matrix decomposition of the input sample covariance matrix. It does this on a block-by-block basis by first computing the sample covariance matrix of the array snapshots within a processing block and then computing the Cholesky decomposition of the sample covariance matrix. The Cholesky 20 decomposition is output to the signal recovery ports 124.1, 124.2, 124.3, which use this information to adapt their weight vectors to separate the cochannel source signals.

The signal model for the narrowband array case is described by the following equation:

$$\mathbf{r}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t),$$

25 where  $\mathbf{r}(t)$  denotes the array signals collected by  $M$  sensors.

We assume that for each block  $N$  snapshots are collected for analysis and that there are  $P$  sources contributing to the measurements. We also assume that the measurement noise,  $\mathbf{n}(t)$ , is spatially white and noise power at each sensor is identical

but unknown and it is denoted by  $\sigma^2$ . The preprocessor 20' first forms the sample covariance matrix from the snapshots according to:

$$\hat{\mathbf{R}} = \frac{1}{N} \sum_{t=1}^N \mathbf{r}(t) \mathbf{r}^H(t).$$

After forming the sample covariance matrix, the Cholesky decomposition is performed:

5

$$\hat{\mathbf{R}} = \mathbf{L} \mathbf{L}^H,$$

where  $\mathbf{L}$  is a lower triangular matrix with positive diagonal terms.  $\mathbf{L}$  is sent to the signal recovery ports 124.1, 124.2, 124.3, as indicated in the drawing.

In the CiCURE structure, there is no controller unit to detect source ON/OFF transitions as in the eCURE system. The signal recovery ports have a 10 predetermined hierarchy or priority order. The first port has highest priority and so on. Therefore, CiCURE is not able to compensate for dynamic changes in the signal environment as can the eCURE algorithm. Each port receives as input the current 15 block steering vector estimates from the ports that are higher in priority, the sensor signal data, and the Cholesky decomposition of the sample covariance matrix for the current block. Each port outputs the recovered signal and associated steering vector for a captured source.

FIG. 16 shows the operations of a single signal recovery port. Suppose the higher-priority ports produce a set of steering vectors for the current block, defined as  $\{\mathbf{a}_1(m), \dots, \mathbf{a}_{k-1}(m)\}$ . The weight vector to produce  $p_k(t)$  for the current block (the  $m$ th block) is determined by modifying the MVDR weights for the  $k$ th port on the previous block by a computation carried out in the  $k$ th port as described next. The first step is to compute Gram-Schmidt orthogonalized weights ( $\mathbf{v}_k(m)$ ) according to:

$$\mathbf{v}_k(m) = \mathbf{w}_k(m-1) - \sum_{l=1}^{k-1} (\mathbf{a}_l^H(m) \mathbf{w}_k) \mathbf{a}_l(m) / \|\mathbf{a}_l(m)\|^2.$$

The port then uses the Gram-Schmidt orthogonalized weights ( $\mathbf{v}_k(m)$ ) to determine the 25 waveform  $p_k(t)$  according to

$$p_k(t) = \mathbf{v}_k^H(m) \mathbf{r}(t).$$

Next, a vector,  $\mathbf{a}_k(m)$ , of sample cross-cumulants involving this waveform is computed having components:

$$[\mathbf{a}_k(m)]_l = \text{cum}(p_k(t), p_k^*(t), p_k^*(t), \mathbf{r}_l(t)), \quad 1 \leq l \leq M,$$

in which,  $[\mathbf{a}_k(m)]_l$  is the  $l$ th component of  $\mathbf{a}_k(m)$ . This vector provides an estimate of a 5 source steering vector and is sent to all the ports that have lower priority than the  $k$ th port and the optional direction-finding unit. In addition, the MVDR weight vector for the  $k$ th port is determined using  $\mathbf{a}_k$  and  $\mathbf{L}$ .

The MVDR weight vector is computed in a two-step procedure that exploits the lower triangular structure of the Cholesky decomposition. First, the 10 temporary solution,  $\mathbf{u}_k$  is computed by solving the linear system of equations:

$$\mathbf{L}\mathbf{u}_k(m) = \mathbf{a}_k(m).$$

Next, the MVDR weights are computed by solving the second linear system:

$$\mathbf{L}^H \mathbf{w}_k(m) = \mathbf{u}_k(m) / \|\mathbf{u}_k(m)\|.$$

It is necessary to maintain phase continuity with the weights of the previous block. 15 This requirement resolves the complex phase ambiguity inherent in the blind signal separation problem, which would otherwise cause "glitches" in the recovered signals at the block boundaries. Therefore, before using the weight vector  $\mathbf{w}_k(m)$  estimate the signal waveform, the complex phase ambiguity is resolved by computing the scale factor:

$$20 \quad c_k(m) = \mathbf{w}_k^H(m) \mathbf{w}_k(m-1) / \|\mathbf{w}_k^H(m) \mathbf{w}_k(m-1)\|,$$

and then scaling the MVDR weights according to:

$$\mathbf{w}_k(m) = c_k(m) \mathbf{w}_k(m).$$

This operation forces the current and previous block signal extraction weights to have a real inner product (i.e., no abrupt phase rotation at the block boundary). This method 25 eliminates block-to-block phase discontinuities, leaving only a bulk phase rotation ambiguity that is constant over all blocks recovered by the port. This bulk phase rotation is unimportant to the recovery of analog AM and FM modulated signals; however, for digital modulations, its removal is desired. Section A subsequent section

on phase rotation equalization presents a method for doing so. For now, we skip over this minor detail.

Using the modified MVDR weights, the waveform estimate is computed according to:

$$5 \quad g_k(t) = \mathbf{w}_k^H \mathbf{r}(t)$$

The recovered waveform is available for subsequent processing, which may consist of recording of the predetected waveform, demodulation, signal recognition, or other operations.

The current block weights are fed into a one-block delay unit which

10 makes them available to the Gram-Schmidt orthogonalization unit as the initial weights for processing the next block. Key characteristics of this implementation are that the iterative convergence of the CURE algorithm is realized over several blocks instead of within a single block, and high-priority ports converge sooner than low-priority ports.

15 **5.0 Alternate Embodiment Using Pipelined Cumulant Recovery (pipeCURE):**

This section describes a variant or extension of the eigendecomposition-based CURE (eCURE) system, which will be called the pipelined eigenCURE (pipeCURE) system. The eigenCURE (eCURE) algorithm analyzes measurements on a block by block basis and has dynamic capabilities to eliminate port switching and port

20 allocation in the case of transient sources. Received signal data are filtered or transformed by a prewhitening operation before reaching cumulant based signal separation processing. eCURE (described in Section 3.0) has several advantages over the covariance-inversion CURE (CiCURE) (described in Section 4.0), which uses covariance-inversion instead of eigendecomposition:

25

- It has better signal separation performance (i.e., better crosstalk rejection at port outputs).
- It has guaranteed fast convergence, specifically a superexponential convergence rate which is mathematically guaranteed.
- It has improved port stability which helps minimize random port switching.

- It can operate with a much wider range of input signal strengths.

This last property is particularly useful when trying to recover a weak signal in the presence of strong interfering signals.

5 The pipeCURE system "pipelines" the eCURE algorithm in order to have:

- Simpler implementation (no feedback between operational blocks).
- An ability to iterate more times over one block of data.
- An option to use further eigendecompositions to improve results.

## 10 5.1 Overview of the pipeCURE Signal Separator:

The pipeCURE signal separator has three main components, which are shown in FIG. 17: a preprocessor unit 120, which is basically the same as in the eCURE system, a cumulant matrix computer 240, and a multiple port signal recovery unit 242. In addition, there are two optional units: the demodulators 128, to complete 15 the recovery of the separated signals for the purpose of recording and the direction-finding (DF) search unit 172 to provide copy-aided directions of arrival on output line 174.

### 5.2 Preprocessor Unit:

20 The preprocessor 120 performs a block-by-block analysis of the element array snapshots, determining the eigenvectors, number of signal sources, and signal subspace of the received array measurement data. It filters the received array data, transforming it from the  $M$ -dimensional sensor space to the  $P$ -dimensional signal subspace. In so doing, the steering vectors of the transformed sources are made 25 orthogonal to each other in the range of this projection, and the transformed source powers are made equal (at high signal-to-noise ratios). The details of the preprocessor operation were described in Section 3.0 in relation to the eCURE system

### 5.3 Cumulant Matrix Computer:

In this section, we introduce the cumulant matrix computer, a unit that computes the statistics as required by the iterative blind signal separation processor. The cumulant matrix computer computes a  $P^2 \times P^2$  (here we assume the number of sources and its estimate are identical) cumulant matrix  $\mathbf{C}$  is defined as:

$$\mathbf{C}(P \cdot (i-1) + j, P \cdot (k-1) + l) = \text{cum}(\mathbf{y}_i^*(t), \mathbf{y}_j(t), \mathbf{y}_k(t), \mathbf{y}_l^*(t)) \quad 1 \leq i, j, k, l \leq P$$

With finite samples, this matrix can be estimated as:

$$\begin{aligned} \mathbf{C}(P \cdot (i-1) + j, P \cdot (k-1) + l) = & \frac{1}{N} \sum_{t=1}^N \mathbf{y}_i^*(t) \mathbf{y}_j(t) \mathbf{y}_k(t) \mathbf{y}_l^*(t) \\ & - \frac{1}{N^2} \sum_{t_1=1}^N \mathbf{y}_i^*(t_1) \mathbf{y}_j(t_1) \sum_{t_2=1}^N \mathbf{y}_k(t_2) \mathbf{y}_l^*(t_2) \\ & - \frac{1}{N^2} \sum_{t_1=1}^N \mathbf{y}_i^*(t_1) \mathbf{y}_k(t_1) \sum_{t_2=1}^N \mathbf{y}_j(t_2) \mathbf{y}_l^*(t_2) - \frac{1}{N^2} \sum_{t_1=1}^N \mathbf{y}_i^*(t_1) \mathbf{y}_l^*(t_1) \sum_{t_2=1}^N \mathbf{y}_j(t_2) \mathbf{y}_k(t_2) \\ 1 \leq i, j, k, l \leq P \end{aligned}$$

in which the signal vector  $\mathbf{y}(t)$  is defined as:

$$\mathbf{y}(t) = \mathbf{T}^H \mathbf{r}(t), \quad \text{where} \quad \mathbf{T} \triangleq \mathbf{E}_s \left( \Lambda_s - \sigma_n^2 \mathbf{I} \right)^{-1/2} = \mathbf{U} \mathbf{S}^{-1}$$

### 5.4 Multiple Port Signal Recovery Unit:

The multiple port signal recovery unit 242, receives as inputs the preprocessed array measurement  $\mathbf{y}(t)$ , the cumulant matrix  $\mathbf{C}$  the eigenstructure  $(\mathbf{E}, \Lambda)$  derived from the array measurements in the preprocessor 120 and the estimated number of sources ( $P_s$ ) generated in the preprocessor. Using these input signals, the multiple port signal recovery unit derives recovered signals for output on lines 132 and steering vectors for output on lines 170, in accordance with the following equations and steps:

(a) Inputs to multiple port signal recovery unit:

- Number of sources,  $P_s$ .
- Transformation matrix  $\mathbf{T} \triangleq \mathbf{E}_s \left( \Lambda_s - \sigma_n^2 \mathbf{I} \right)^{-1/2}$

- Preprocessed signals:  $y(t) = T^H r(t)$
- Eigenstructure of the covariance matrix:  $\{E_s, \Lambda_s, \sigma_n^2\}$
- Initial estimates of the steering vectors for sources stored as the columns of  $\tilde{A}$ .
- Cumulant matrix  $C$ :

5

$$C(P \cdot (i-1) + j, P \cdot (k-1) + l) = \text{cum}(y_i^*(t), y_j(t), y_k(t), y_l^*(t)) \quad 1 \leq i, j, k, l \leq P$$

(b) Outputs from multiple port signal recovery unit:

- Estimated steering vector  $\hat{A}$  that will be used in the next block as a starting point (in place of  $\tilde{A}$ ).
- Recovered signals for the analysis block,  $\hat{s}(t)$ .

15

(c) Processing in the multiple port signal recovery unit:

1. Transformation of Steering Vectors: Project the steering matrix estimate onto the reduced dimensional space by the transformation matrix  $T$ :

$$\tilde{B} = T^H \tilde{A}$$

20 2. Cumulant Strength Computation: Normalize the norm of each column of  $\tilde{B}$  and store the results in  $\tilde{V}$ , and then compute the cumulant strength for each signal extracted by the weights using the matrix vector multiplication:

$$\tilde{v}_m = \tilde{b}_m / \|\tilde{b}_m\|, \quad \text{where } \tilde{v}_m (\tilde{b}_m) \text{ is the } m\text{th column of } \tilde{V} (\tilde{B}).$$

$$O_m = \left| (\tilde{v}_m^* \otimes \tilde{v}_m)^H C (\tilde{v}_m^* \otimes \tilde{v}_m) \right|, \quad \text{for } 1 \leq m \leq P.$$

25 3. Priority Determination: Reorder the columns of  $\tilde{V}$  and form the matrix  $\tilde{W}$ , such that the first column of  $\tilde{W}$  yields the highest cumulant strength, and the last column of  $\tilde{W}$  yields the smallest cumulant strength.

Columns of  $\tilde{V}$  in descending cumulant strength  $\rightarrow \tilde{W}$

4. Capture of the  $k$ th source: Starting with the  $k$ th column of  $\tilde{\mathbf{W}}$ , proceed with the double power method followed by Gram-Schmidt orthogonalization with respect to higher priority columns of  $\tilde{\mathbf{W}}$ , i.e., for column  $k$ :

$$\tilde{\mathbf{w}}_k(b+1) = \alpha_{b+1} \cdot (\tilde{\mathbf{w}}_k^*(b) \otimes \mathbf{I}_p)^H \mathbf{C} (\tilde{\mathbf{w}}_k^*(b) \otimes \tilde{\mathbf{w}}_k(b)), \quad b \text{ is the iteration number,}$$

5 where the constant  $\alpha_{b+1}$  is chosen so that the norm of  $\tilde{\mathbf{w}}_k(b+1)$  is unity and  $b$  is the iteration number. This operation is followed by the Gram-Schmidt orthogonalization:

$$\tilde{\mathbf{w}}_k(b+1) = \beta_{b+1} \cdot \left( \tilde{\mathbf{w}}_k(b+1) - \sum_{l=1}^{k-1} \mathbf{w}_l \cdot (\mathbf{w}_l^H \tilde{\mathbf{w}}_k(b+1)) \right), \quad \text{since } \|\mathbf{w}_l\| = 1,$$

where the constant  $\beta_{b+1}$  is chosen so that the norm of  $\tilde{\mathbf{w}}_k(b+1)$  is unity. In the last expression,  $\mathbf{w}_l$  denotes the final weight vector with source of priority  $l$ .

10 5. Capture of the remaining sources: Repeat step 4, for each column for a predetermined  $K$  times. After iterations are complete for the  $k$ th column, declare the resultant vector as  $\mathbf{w}_k$ , and proceed with the remaining columns. After all sources are separated, form the matrix  $\mathbf{W}$  that consists of  $\mathbf{w}_k$ 's as its columns.

Converged weight vectors  $\mathbf{w}_k$ 's  $\rightarrow$  form the columns of  $\mathbf{W}$ .

15 6. Port Association: After all the power method and Gram-Schmidt iterations are complete, we compare the angle between columns of  $\mathbf{W}$  and the columns of  $\tilde{\mathbf{V}}$ .

Calculate the absolute values of the elements of the matrix  $\mathbf{Z} = \mathbf{W}^H \tilde{\mathbf{V}}$ .

Take the arccosine of each component of  $\mathbf{Z}$ .

20 To find the port number assigned to the first column of  $\mathbf{W}$  in the previous block, simply take the index of the largest element of the first row of the matrix  $\mathbf{Z}$ .

For the second column of  $\mathbf{W}$ , we proceed the same way except this time we do not consider previously selected port for the first column. Using this rule, we 25 reorder the columns of  $\mathbf{W}$ , such that there is no port switching involved.

Reorder the columns of  $\mathbf{W}$ , based on  $\mathbf{Z} \rightarrow$  results in  $\hat{\mathbf{V}}$ .

7. Steering Vector Adjustment: Due to the blindness of the problem, estimated steering vectors are subject to arbitrary gain and phase ambiguities. The gain ambiguities are corrected by the unit amplitude constraint on the columns of  $\hat{V}$ . However, this does not prevent phase modulations on the columns of this matrix. To maintain this continuity, we compute the inner product of each column of  $\hat{V}$  with the corresponding column in  $\tilde{V}$  and use the resulting scalar to undo the phase modulation, i.e.,

$$\varepsilon_m = \text{angle}(\tilde{V}_m^H V_m), \text{ and } v_m = v_m \cdot \exp(-j\varepsilon_m).$$

8. Backprojection: In order to use the current steering vector estimates for the next processing block, we need to backproject the steering vector estimates for the reduced dimensional space to the measurement space. This yields the estimate of the steering matrix and can be accomplished as:

$$\hat{A} = E_s (\Lambda_s - \hat{\sigma}^2 I_{P_s})^{1/2} \hat{V}.$$

$\hat{A}$  will be used in the next block as  $\tilde{A}$  as an estimate of the steering matrix in the first step of the multiple port signal extraction unit.

9. Beamforming: It is important to note that beamforming for  $P$  sources requires a matrix multiplication of two matrices: the  $\hat{V}$  matrix that is  $P$  by  $P$ , and the reduced dimensional observation matrix  $y(t)$ , which is  $P$  by  $N$ , where  $N$  is the number of snapshots. Usually  $N$  is larger than  $P$  and this matrix multiplication may take a long time because of its size. Therefore, it may be appropriate to do final beamforming in another processor since it does not introduce any feedback. Final beamforming is accomplished as:

$$\hat{s}(t) = \hat{V}^H y(t)$$

The estimated signals will be sent to the correct post processing units because of the orderings involved.

#### 6.0 Steering Vector Tracking Method For Situations Having Relative Motion:

For situations in which there is relative motion of the source, receiving array, or multipath reflectors, it is desirable to generalize the CURE algorithms to exploit or compensate for the motion. One rather complicated way of doing this is to 5 use an extended Kalman filter to track the changes in the generalized steering vectors derived by the CURE algorithms. Here we present a simpler method which merely involves using a variant of the iterative update equation used in the CURE algorithms. We present two such variants of the update equations, called  $\alpha$ - $\beta$ CURE and  $\mu$ CURE, that can be used principally to provide an improved initial weight vector for each block 10 of array samples (snapshots). These update equations can be used with any of the CURE algorithms discussed in previous sections (CiCURE, eCURE, pipeCURE). Consequently  $\alpha$ - $\beta$ CURE and  $\mu$ CURE are not independent stand-alone algorithms, but rather are enhancements to CiCURE, eCURE, and pipeCURE that provide greater stability and less port-switching in dynamic situations.

15 The iterative update equations are given by:

$$w_{k+1} = \alpha w_k + \beta \text{vect}[\text{cum}(\dots, \dots)] \quad (\alpha\text{-}\beta\text{CURE})$$

$$w_{k+1} = (1-\mu) w_k + \mu \text{vect}[\text{cum}(\dots, \dots)] \quad (\mu\text{CURE})$$

$$= w_k + \mu [\text{vect}[\text{cum}(\dots, \dots)] - w_k].$$

These iterative update equations may be compared to the standard iterative update 20 equation presented in previous sections for CiCURE, eCURE, and pipeCURE.

$$w_{k+1} = \text{vect}[\text{cum}(\dots, \dots)]. \quad (\text{CiCURE, eCURE, pipeCURE}).$$

In these equations,  $k$  is a time index, and  $w_k$  is the linear combiner weight vector that converges to the generalized steering vector of one of the input source signals. The iteration on the index  $k$  is on individual snapshots or block of 25 snapshots occurring through time, as opposed to multiple iterations within a block. The  $\alpha$ - $\beta$  and  $\mu$  update method does not preclude iteration within a block. Indeed, within-block iteration can be used in conjunction with block-to-block updating or initialization. Generally, there is no advantage to using the  $\alpha$ - $\beta$  or  $\mu$  update equations for within-block iteration. Within-block iteration should be done by the standard

update equation. The  $\alpha$ - $\beta$  and  $\mu$  update equations are best used for block-to-block updating, that is, to initialize a block's weight vector based on the final converged weight vector from the previous block.

Two equivalent forms are given for the  $\mu$ CURE update equation. As is discussed below, the first form is most convenient when the purpose is to predict ahead, whereas the second form is most convenient when the purpose is to average previous data with new data. Although  $\alpha$ - $\beta$ CURE and  $\mu$ CURE appear to involve different update equations, the algorithms are equivalent provided there is a renormalization of the weight vector at every iteration. Because a weight vector renormalization is always used in the iterative steps to prevent the weight vector from shrinking monotonically,  $\alpha$ - $\beta$ CURE and  $\mu$ CURE are equivalent.

$\alpha$ - $\beta$ CURE and  $\mu$ CURE updating can be used for determining the initial EGSV(s) of a block of samples subject to eCURE or pipeCURE processing. When used with eCURE, the block initialization can be performed in either the  $M$ -dimensional sensor space or the  $P$ -dimensional signal subspace. FIG 19 and FIG 20 show these two cases, respectively. The application of  $\alpha$ - $\beta$ CURE and  $\mu$ CURE to CiCURE is similar to FIG 19 but is not shown.

FIG. 19 shows the relations among various vectors in one cycle of the  $\mu$ CURE update operating in the  $M$  dimensions of the sensor space. Five vectors are shown.  $w_k$  is the current weight vector at time  $k$  and is also the current estimate of the generalized steering vector  $a_k$ . The generalized steering vector at time  $k+1$  is denoted  $a_{k+1}$ .  $a_{k+1}$  is the generalized steering vector of which  $w_{k+1}$  is an approximation. The cumulant vector  $cum = vect[cum(.,.,.,.)]$  is represented as a vector emanating from the origin. The scaled difference vector  $\mu[cum - w_k]$  is shown as a vector originating at the tip of  $w_k$  and extending through the tip of  $cum$ . The tip of this vector defines  $w_{k+1}$ .

For the case shown,  $\mu$  is greater than unity, and the algorithm is anticipatory. This form of the  $\mu$ CURE update is useful when the purpose is to predict

a generalized steering vector that is varying with time. It is instructive to think of the  $\mu$ CURE update as an equation of motion:

$$\text{New Position} = \text{Old Position} + \text{Velocity} \times \text{Elapsed Time},$$

where *New Position* is identified with  $w_{k+1}$ ; *Old Position* is identified with  $w_k$ ; *Velocity* 5 is identified with  $[\text{cum} - w_k]$ ; and *Elapsed Time* is identified with  $\mu$ .

Conversely, if  $\mu$  is less than unity, the  $\mu$ CURE update functions as an averager rather than a predictor, putting weight  $(1-\mu)$  on the current weight vector  $w_k$  and weight  $\mu$  on *cum* which is an estimate of the generalized steering vector  $a_{k+1}$  (or its projection  $b_{k+1}$ ). In this case, the tip of *cum* would lie to the right of  $w_{k+1}$ , and the 10 scaled difference vector  $\mu[\text{cum} - w_k]$  would point to, but not pass through, *cum*.

FIG. 20 similarly shows the vector relations for one cycle of the  $\mu$ CURE update when the iteration is performed in the  $P$  dimensions of the signal subspace. The vectors are similar to those in FIG. 19 with the key difference being that  $b_k$  is the projection of the generalized steering vector  $a_k$  into the signal subspace, 15 and  $w_{k+1}$  approximates  $b_{k+1}$ , the projection of  $a_{k+1}$ . At the conclusion of the iterations, the estimated generalized steering vector may be obtained by backprojecting the terminal weight vector  $w$  into the  $M$  dimensional sensor space.

$\alpha-\beta$  and  $\mu$  iterative updating has an advantage in the situation where signal sources are persistent but moving (i.e., non-static geometry). CiCURE, 20 eCURE, and pipeCURE are formulated in the batch-processing mode (i.e., array snapshots are processed one block of samples at a time) assuming the source geometry is static during a block. With these algorithms, only small changes in source geometry are allowed to occur from one block to the next.  $\alpha-\beta$  CURE and  $\mu$ CURE accommodate greater changes from block to block by providing for tracking of the 25 generalized steering vectors via the  $\alpha-\beta$  tracking method, which is well known in the sonar and radar engineering literature.

In summary,  $\alpha-\beta$ CURE and  $\mu$  iterative updating have tracking capability inherently built in which can be used to improve the performance of CiCURE, eCURE, and pipeCURE in situations in which EGSVs are changing

dynamically. This tracking capability enables the adaptation to geometrical changes that occur gradually over time. Abrupt changes, like the appearance of new signals or disappearance of old signals, and attendant port switching are a different problem. Detection logic is still required to mitigate port switching caused by abrupt changes.

5

### 7.0 Alternate Embodiment Using Direct or Analytic Computation:

Unlike the iterative methods presented in previous sections, this section presents a method for separating signals that is non-iterative. It is, in fact, a closed form, analytic solution for computing the cumulant vectors and generalized steering 10 vectors without the need for iteration. Because the method is non-iterative, the issues of convergence and convergence rate are no longer of concern. Convergence is both assured and instantaneous.

In the direct method, the generalized steering vectors for a small number of sources (two in this example) are computed directly as set forth below, using one of 15 two computational methods:

#### Steps of Operation for Method 1:

- Compute the covariance matrix  $\mathbf{R}$  for  $M$  channel measurements:

$$\mathbf{R} = \frac{1}{N} \sum_{t=1}^N \mathbf{r}(t) \mathbf{r}^H(t)$$

20 • Compute the eigendecomposition for  $\mathbf{R}$ :

$$\mathbf{R} = \mathbf{E}_s \mathbf{A}_s \mathbf{E}_s^H + \sigma_n^2 \mathbf{E}_n \mathbf{E}_n^H$$

- Compute the transformation matrix  $\mathbf{T}$ :

$$\mathbf{T} = \mathbf{E}_s \left( \mathbf{A}_s - \sigma_n^2 \mathbf{I} \right)^{-1/2}$$

- Preprocess the measurements by the transformation matrix:

25

$$\mathbf{y}(t) = \mathbf{T}^H \mathbf{r}(t)$$

- Compute the four by four cumulant matrix  $\mathbf{C}$  from  $\mathbf{y}(t)$ :

$$\mathbf{C}(P \cdot (i-1) + j, P \cdot (k-1) + l) = \text{cum}(\mathbf{y}_i^*(t), \mathbf{y}_j^*(t), \mathbf{y}_k^*(t), \mathbf{y}_l^*(t)) \quad 1 \leq i, j, k, l \leq 2$$

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- From its definition, the  $\mathbf{C}$  matrix can be decomposed as:

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_{11} & \mathbf{C}_{12}^H \\ \mathbf{C}_{21} & \mathbf{C}_{22} \end{bmatrix}$$

in which the three matrices  $\{\mathbf{C}_{11}, \mathbf{C}_{22}, \mathbf{C}_{21}\}$  are defined (because of prewhitening and 5 circular symmetry assumption):

$$\mathbf{C}_{11} = \begin{bmatrix} E\{|y_1(t)|^4\} - 2 & E\{|y_1(t)|^2 y_1(t) y_2^*(t)\} \\ E\{|y_1(t)|^2 y_2(t) y_1^*(t)\} & E\{|y_1(t)|^2 |y_2(t)|^2\} - 1 \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \\ c_2 & c_3 \end{bmatrix}$$

$$\mathbf{C}_{21} = \begin{bmatrix} E\{|y_1(t)|^2 y_1(t) y_2^*(t)\} & E\{(y_1(t) y_2^*(t))^2\} \\ E\{|y_1(t)|^2 |y_2(t)|^2\} - 1 & E\{y_1(t) y_2^*(t) |y_2(t)|^2\} \end{bmatrix} = \begin{bmatrix} c_2 & c_4 \\ c_3 & c_5 \end{bmatrix}$$

$$10 \quad \mathbf{C}_{22} = \begin{bmatrix} E\{|y_1(t)|^2 |y_2(t)|^2\} - 1 & E\{|y_2(t)|^2 y_1(t) y_2^*(t)\} \\ E\{|y_2(t)|^2 y_2(t) y_1^*(t)\} & E\{|y_2(t)|^4\} - 2 \end{bmatrix} = \begin{bmatrix} c_3 & c_5 \\ c_5 & c_6 \end{bmatrix}$$

- Construct the fourth-order polynomial in terms of the complex variables  $\{v_1, v_2\}$ .

$$\frac{v_1}{v_2} = \frac{|v_1|^2 (c_1 v_1 + c_2 v_2) + |v_2|^2 (c_3 v_1 + c_5 v_2) + v_1^* v_2 (c_2 v_1 + c_4 v_2) + v_2^* v_1 (c_2 v_1 + c_3 v_2)}{|v_1|^2 (c_2 v_1 + c_3 v_2) + |v_2|^2 (c_5 v_1 + c_6 v_2) + v_1^* v_2 (c_3 v_1 + c_5 v_2) + v_2^* v_1 (c_4 v_1 + c_5 v_2)}.$$

15 This requires the computation of the cumulants  $\{c_1, \dots, c_6\}$  defined in the above item from the measurements.

- Solve the polynomial for  $\{v_1, v_2\}$ . There is one trivial solution  $\{v_1 = v_2 = 0\}$ . Also note that if the vector  $(v_1, v_2)^T$  is a solution, then the vector  $(-v_2^*, v_1)^T$  is also a solution.

20 • Evaluate the resultant cumulant strengths from the solutions to the polynomial:

$$((\mathbf{v}^* \otimes \mathbf{v})^H \mathbf{C} (\mathbf{v}^* \otimes \mathbf{v})), \mathbf{v} = [v_1, v_2]^H.$$

- Determine the solution for the polynomial that results in the highest cumulant strengths to estimate sources. Let this be  $(v_1, v_2)^T$ . Then,  $(-v_2^*, v_1)^T$  is the the second solution.
- For each accepted solution  $v$ , we can find the corresponding steering vector in the  $M$  dimensional sensor space:

$$\mathbf{a} = \mathbf{E}_s \left( \Lambda_s - \sigma_n^2 \right)^{1/2} \mathbf{v}$$

- Once the steering vector estimates are found as in the previous step:
  1. Port association, and
  2. Waveform continuity,
 can be implemented as described in Section 5.0 (pipeCURE).

### Steps of Operation for Method 2

- Compute the covariance matrix  $\mathbf{R}$  for  $M$  channel measurements:

$$\mathbf{R} = \frac{1}{N} \sum_{t=1}^N \mathbf{r}(t)\mathbf{r}^H(t)$$

15 • Compute the eigendecomposition for  $\mathbf{R}$ :

$$\mathbf{R} = \mathbf{E}_s \mathbf{\Lambda}_s \mathbf{E}_s^H + \sigma_n^2 \mathbf{E}_n \mathbf{E}_n^H$$

- Compute the transformation matrix  $T$ :

$$\mathbf{T} = \mathbf{E}_s \left( \Lambda_s - \sigma_s^2 \mathbf{I} \right)^{-1/2}$$

- Preprocess the measurements by the transformation matrix:

$$\mathbf{v}(t) = \mathbf{T}^H \mathbf{r}(t)$$

after which the measurements take the form:

$$\mathbf{y}(t) \equiv \mathbf{T}^H \mathbf{r}(t) \equiv \mathbf{b}_1 s_1(t) / \sigma_1^2 + \mathbf{b}_2 s_2(t) / \sigma_2^2 + \mathbf{e}(t)$$

Because of prewhitening, we have the following result for the steering vectors for the two sources in the two dimensional space:

$$\mathbf{b}_1 = \begin{bmatrix} \cos\theta \\ \sin\theta e^{-i\phi} \end{bmatrix}, \quad \mathbf{b}_2 = \begin{bmatrix} -\sin\theta e^{-i\phi} \\ \cos\theta \end{bmatrix}, \quad \|\mathbf{b}_1\| = \|\mathbf{b}_2\| = 1, \quad \|\mathbf{b}_2^H \mathbf{b}_1\| = 0.$$

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- Construct the three by two matrix  $\mathbf{F}$  using five of the six cumulants:

$$\mathbf{F} = \begin{bmatrix} c_1 & c_2 \\ c_2 & c_3 \\ c_4 & c_5 \end{bmatrix} = \begin{bmatrix} E\{[y_1(t)]^4\} - 2 & E\{[y_1(t)]^2 y_1(t) y_2(t)\} \\ E\{[y_1(t)]^2 y_2(t) y_1^*(t)\} & E\{[y_1(t)]^2 [y_2(t)]^2\} - 1 \\ E\{[y_1^*(t) y_2(t)]^2\} & E\{y_1^*(t) y_2(t) [y_2(t)]^2\} \end{bmatrix}$$

which can be decomposed into the following three matrices:

$$\mathbf{F} = \begin{bmatrix} 1 & 1 \\ \frac{\sin\theta}{\cos\theta} e^{j\phi} & -\frac{\cos\theta}{\sin\theta} e^{j\phi} \\ \left(\frac{\sin\theta}{\cos\theta} e^{j\phi}\right)^2 & \left(-\frac{\cos\theta}{\sin\theta} e^{j\phi}\right)^2 \end{bmatrix} \begin{bmatrix} \frac{\gamma_{4,1}}{(\sigma_i^2)^2} \cdot \cos^4 0 & 0 \\ 0 & \frac{\gamma_{4,2}}{(\sigma_i^2)^2} \cdot \sin^4 0 \end{bmatrix} \begin{bmatrix} 1 & \frac{\sin 0}{\cos 0} e^{-j\phi} \\ 1 & -\frac{\cos 0}{\sin 0} e^{-j\phi} \end{bmatrix}$$

$$\mathbf{F} = \mathbf{G} \mathbf{D} \mathbf{H}$$

- Also form the four by four cumulant matrix  $\mathbf{C}$ :

$$\mathbf{C}(P \cdot (i-1) + j, P \cdot (k-1) + l) = \text{cum}(y_i^*(t), y_j(t), y_k(t), y_l^*(t)) \quad 1 \leq i, j, k, l \leq 2$$

The symmetries involved in this matrix reduces the number of distinct cumulants to six. In addition, five of the six cumulants necessary are already computed when we formed  $\mathbf{F}$ .

- Compute the Singular Value Decomposition (SVD) of the matrix  $\mathbf{F}$ :

1. If the rank of  $\mathbf{F}$  is zero, then source separation is not possible.

2. If the rank of  $\mathbf{F}$  is one, then the principal eigenvector can be used to separate sources: assume  $\mathbf{e}_1$  is the principal eigenvector of  $\mathbf{F}$ , and let its components are defined as:

$$15 \quad \mathbf{e}_1 = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}, \quad |\alpha_1|^2 + |\alpha_2|^2 + |\alpha_3|^2 = 1$$

Then, we can obtain the estimate of the first source, using:

$$g_1(t) = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}^H \mathbf{y}(t)$$

and the second source waveform can be estimated using:

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$$g_2(t) = \begin{bmatrix} -\alpha_2^* \\ \alpha_1 \end{bmatrix}^H \mathbf{y}(t)$$

3. If the rank of  $\mathbf{F}$  is two, then the null eigenvector can be used to separate sources together with a solution of a quadratic equation: let  $\mathbf{x}$  denote the 3 by 1 vector that is orthogonal to the columns of  $\mathbf{F}$  (which can be obtained using SVD or QR decomposition of  $\mathbf{F}$ ):

$$\mathbf{x}^H \mathbf{F} = 0, \quad \mathbf{x} = [x_1, x_2, x_3]^T$$

Then, due to the Vandermonde structure of the columns of  $\mathbf{G}$ , we can obtain the parameters  $\left\{ \frac{\sin\theta}{\cos\theta} e^{j\theta}, -\frac{\cos\theta}{\sin\theta} e^{j\theta} \right\}$ , as the roots of the quadratic equation:

$$10 \quad \mathbf{x}^H \mathbf{z} = 0, \quad \mathbf{z} = [z_1, z_2, z_3]^T \rightarrow x_1^* + x_2^* z + x_3^* z^2 = 0$$

Since we know the roots of the above equation should be  $\left\{ \frac{\sin\theta}{\cos\theta} e^{j\theta}, -\frac{\cos\theta}{\sin\theta} e^{j\theta} \right\}$ , and we have the weight vectors to separate the sources as:

$$g_1(t) = \begin{bmatrix} 1 \\ \frac{\sin\theta}{\cos\theta} e^{j\theta} \end{bmatrix}^H \mathbf{y}(t) = s_1(t) / (\sigma_1^2 \cos\theta) + 0 \cdot s_2(t) + \begin{bmatrix} 1 \\ \frac{\sin\theta}{\cos\theta} e^{j\theta} \end{bmatrix}^H \mathbf{e}(t)$$

$$g_2(t) = \begin{bmatrix} 1 \\ -\frac{\cos\theta}{\sin\theta} e^{j\theta} \end{bmatrix}^H \mathbf{y}(t) = s_2(t) e^{-j\theta} / (\sigma_2^2 \sin\theta) + 0 \cdot s_1(t) + \begin{bmatrix} 1 \\ -\frac{\cos\theta}{\sin\theta} e^{j\theta} \end{bmatrix}^H \mathbf{e}(t)$$

15 In addition, we can normalize the weights to conform to the structure of the problem:

$$\mathbf{v}_1 = \beta_1 \begin{bmatrix} 1 \\ \frac{\sin\theta}{\cos\theta} e^{j\theta} \end{bmatrix}, \quad \mathbf{v}_2 = \beta_2 \begin{bmatrix} 1 \\ -\frac{\cos\theta}{\sin\theta} e^{j\theta} \end{bmatrix}$$

in which  $\{\beta_1, \beta_2\}$  are determined to make  $\|\mathbf{v}_1\| = \|\mathbf{v}_2\| = 1$ .

- After the weights for signal separation are determined, then it is possible to compute cumulant strengths using:  $\{(\mathbf{v}^* \otimes \mathbf{v})^H \mathbf{C} (\mathbf{v}^* \otimes \mathbf{v})\}$ ,  $\mathbf{v} = [\mathbf{v}_1, \mathbf{v}_2]^H$  is one of the weight vectors.
- 5     • For each solution represented by  $\mathbf{v}$ , we can find the corresponding steering vector in the  $M$  dimensional sensor space:
 
$$\mathbf{a} = \mathbf{E}_s (\Lambda_s - \sigma_n^2)^{1/2} \mathbf{v}$$
  - Once the steering vector estimates are found as in the previous step:
    1. Port association, and
    - 10     2. Waveform continuity

can be implemented as described in Section 5.0 (pipeCURE).

## 8.0 Separation Capacity and Performance When Overloaded:

When the number of incident signals exceeds the capacity of the system 15 to separate signals, one would expect system performance to degrade. Unlike some other cochannel signal separation methods, the present invention is able to operate under such overload conditions.

Cochannel signal separation systems are designed to be able to separate and recover signals provided the number of cochannel signals incident on the array 20 does not exceed a number that defines the separation capacity of the system. In the present invention, the separation capacity is equal to the number of sensors  $M$  in the receiving array. Consequently, a cochannel signal separation system based upon this method can have no more than  $M$  output ports. Of course, the number of output ports can be less than  $M$ . For instance, a system can have  $P$  output ports, where  $P < M$ . In 25 this case the system could recover each of  $P$  signals from among  $M$  signals incident on the array. Each of the  $P$  signals is recovered by a different set of beamformer weights. Each such set or weight vector defines a sensor directivity pattern having  $M-1$  nulls.

Next consider cochannel signals received at the receiving array consisting of a mixture of coherent and noncoherent multipath components. A

complete description of how CURE algorithms behave in the presence of multipath is given in Section 9.0. In brief, signals with noncoherent multipath components are recovered on more than one output port. Each output port is associated with a single generalized steering vector. The system of the invention automatically creates groups 5 of mutually coherent multipath arrivals and a different generalized steering vector is formed for each such group. Each group is treated as an independent signal and counts as one signal against the capacity  $M$ . The maximum number of such noncoherent groups that can be incident on the array for which the system can perform separation and recovery equals the separation capacity. In the present invention, this capacity 10 equals the number of array elements  $M$ .

In overload situations, the cumulant optimization or iteration, which is the basis of the invention, still converges to a generalized steering vector of a signal or noncoherent multipath group. Consequently, the system of the invention determines up to  $M$  generalized steering vectors from which beamforming weights are computed and 15 which can form up to  $M-1$  generalized nulls. However, because the number of signals is greater than capacity, it is not possible to recover a given signal while simultaneously rejecting all other signals by means of generalized nulls. In particular, there are  $P-M$  excess signals (or  $G-M$  noncoherent groups) that leak through the beamformers for the recovered signals. These excess signals are rejected merely by 20 the sidelobe suppression associated with each beamformer's directivity pattern. The signals that are captured for recovery by the system tend to be the strongest signals, while the excess signals tend to be among the weakest. The excess signals contribute to the noise floor of the output ports. However, their contribution is minimal because of their low relative power and the sidelobe attenuation. Consequently, the recovered 25 signals at the output ports generally have low crosstalk levels and high signal-to-interference-plus-noise ratio (SINR).

FIGS. 21 and 22 illustrate the overload concept diagrammatically. FIG. 21 shows a basestation having a four-element antenna array, which provides input signals to a CURE system for separating received cochannel signals. Because the 30 antenna array has only four elements, the system has a capacity of four channels. The

figure also shows five users, designated User A, User B, User C, User D and User E, all attempting to transmit signals to the basestation array. FIG. 22 shows a directivity pattern associated with the antenna array as conditioned by the CURE system to receive signals from User A. Because the array has only four elements, it can present 5 directivity nulls in only three directions. In the example, the directivity pattern presents a strong lobe in the direction of User A, to receive its signals, and presents its three available nulls toward User B, User D and User E. User C, which produces the weakest and most distant signal, cannot be completely nulled out. Similar directivity patterns will be generated for receiving signals from User B, User D and User E. In 10 each case, the weakest signal (from User C) will not be completely nulled out by the directivity pattern. The system continues to operate, however, and is degraded only in the sense that weaker sources exceeding the system capacity cannot be recovered and will produce some degree of interference with the signals that are recovered.

A general conclusion is that the various embodiments of the invention 15 are tolerant of separation capacity (or number-of-signals) overload conditions. In other words, the various embodiments of the invention are "failsafe" with respect to overload beyond the signal separation capacities, and the ability to separate signals degrades gracefully as the number of signals is increased above the separation capacity. This property distinguishes CURE algorithms from DF-beamforming cochannel signal copy 20 algorithms, such as MUSIC and ESPRIT, which do not function when overloaded. (MUSIC is an acronym for MUltiple Signal Identification and Classification, and ESPRIT is an acronym for Estimation of Signal Parameters via Rotational Invariance Techniques. For more information on these systems, see the papers cited in the "background" section of this specification.

25

## 9.0 Performance of the Invention in the Presence of Multipath:

This section discusses the performance of the CURE systems (CiCURE, eCURE, pipeCURE, etc.) when the signal environment includes multipath propagation. We confine the discussion to the phenomenon known as discrete multipath, as opposed

to continuous volumetric scattering, which is more complicated to describe. However, the statements below apply to volumetric scattering under certain conditions.

Multipath propagation occurs when a signal from a source travels by two or more distinct paths to arrive at a receiving antenna from several directions 5 simultaneously. A novel feature of the present invention is its ability to separate cochannel signals in a multipath signal environment.

Multipath propagation is caused by the physical processes of reflection and refraction. A similar effect is caused by repeater jamming, wherein a signal is received and retransmitted at high power on the same frequency. Repeaters are 10 commonly used in radio communication to fill in shadow zones, such as around hills or inside tunnels, where the communication signal does not propagate naturally. Cochannel repeaters are also used in electronic warfare (EW) systems to "spoof" a radar system by retransmitting a radar signal with a random delay at sufficiently high power to mask the actual radar return. The amount of delay is set in order to cause a 15 false distance to be measured by the radar.

Naturally occurring multipath propagation can consist of a small number of discrete specular reflections, or it can consist of a continuum of reflections caused by scattering from an extended object. The various multipath components arriving at the receiving antenna will generally be somewhat different. Differences among the 20 various multipath components of a given source signal are (1) different directions of arrival (DOAs); (2) different time delays due to the different path lengths traveled; and (3) different Doppler shifts on each multipath component due to motion of the transmit antenna, receive antenna, or reflecting body.

Array-based cochannel signal separation and recovery systems 25 traditionally have difficulty working in a multipath environment (i.e., when the one or more of the arriving signals incident on the array come from several distinct directions simultaneously). For example, most multiple source DF-beamforming signal copy systems generally do not work properly or well in a multipath environment, and special techniques such as spatial smoothing and temporal smoothing must be employed to DF 30 on the individual multipath components of an arriving signal. The resultant system and

processing complexities make DF-based cochannel signal recovery systems largely impractical for reception in signal environments characterized by significant multipath propagation. The cochannel signal separation capability of the CURE family of systems overcomes these limitations.

5 To understand how the CURE system behaves in the multipath context requires understanding the different types of multipath effects and how the system handles each type. In general, multipath arrivals of a source signal can be classified as either coherent or noncoherent depending on whether the arrivals' cross-correlation function computed over a finite time interval is large or small. Thus the designation  
10 coherent or noncoherent is relative to the length of the measurement interval. Coherent multipath components frequently occur in situations where the scattering bodies are near either the transmit or receive antennas and are geometrically fixed or moving at low velocities. Noncoherent multipath is caused by path delay differences and Doppler shift differences that are large compared to the measurement window.

15 The CURE algorithms recover generalized steering vectors as opposed to ordinary steering vectors. An ordinary steering vector is the value of the array manifold at a single angle corresponding to a source's DOA. However in a multipath environment the received wavefield that the array spatially samples is composed of many plane waves for each source signal. Each source, therefore cannot be  
20 characterized by a single DOA or steering vector. We consider how the CURE algorithms behave under three cases:

- Coherent multipath components,
- Noncoherent multipath components,
- Mixtures of coherent and noncoherent multipath components.

25

### 9.1 Performance Against Coherent Multipath:

In a coherent multipath signal environment, the CURE system finds a single steering vector for each independent signal source. However, these steering vectors do not correspond to the ordinary steering vectors, which could be innumerable  
30 in the presence of many multipath scatterers. Rather, the CURE vectors are

generalized steering vectors that correspond to the sum of all the mutually coherent multipath components of a signal source incident on the array. In the case of a finite number of discrete multipaths, the generalized steering vector depends on the relative power levels, phases, and ordinary steering vectors of the multipath components.

5        The CURE signal recovery process is blind to the array manifold. Once the generalized steering vectors for the cochannel sources have been obtained, it is unnecessary to convert them to source directions of arrival (DOAs) by using the array manifold, as would generally be done in a system employing direction finding (DF). Instead, the beamforming weight vectors for signal recovery are computed directly 10 from the generalized steering vectors. This is done by one of two methods: (1) by projecting each generalized steering vector into the orthogonal complement of the subspace defined by the span of the vectors of the other sources (by matrix transformation using the Moore-Penrose pseudo-inverse matrix); or (2) by using the Capon beamformer, also called the Minimum Variance Distortionless Response 15 (MVDR) beamformer in the acoustics literature, to determine the recovery weight vectors from the generalized steering vectors. These solutions are both well known in the signal processing engineering literature. (See, for example, pp. 73-74 of Hamid Krim and Mats Viberg, "Two Decades of Array Signal Processing Research," IEEE Signal Processing Magazine, vol. 13, no. 4, pp. 67-94, July 1996, ISSN 1053-5888, or 20 Norman L. Owsley, "Sonar Array Processing," Chapter 3 of Array Signal Processing, S. Haykin (ed.), Prentice-Hall, 1985, 445 pp., ISBN 0-13-046482-1.) If the generalized steering vectors are determined perfectly, i.e., no estimation error, then the former solution would provide zero crosstalk (or maximum signal-to-interference ratio) among the recovered signals at the beamformer output. The latter solution would 25 provide recovered signals having maximum signal-to-interference-plus-noise ratio (SINR).

Each output port of the CURE-based system has a beamforming weight vector that is orthogonal or nearly orthogonal to the generalized steering vectors of the cochannel signals that are rejected by the output port. Each beamforming weight 30 vector has a corresponding directivity pattern that assigns a gain and phase to every

possible direction of arrival. These directivity patterns can have up to  $N-1$  nulls, where  $N$  is the number of array elements. The nulls can be either physical nulls in prescribed directions-of-arrival (DOAs) or, in the case of coherent multipath, generalized nulls. Generalized nulls are not directional nulls but rather are formed 5 when a directivity pattern assigns gains and phases in the directions of the coherent multipath components of an interfering signal such that the components sum to zero. Generalized nulls have a major advantage over physical nulls for combating cochannel interference from coherent multipath because fewer degrees of freedom (i.e., fewer array elements) are required to cause coherent multipath components to sum to zero 10 than are required to directionally null each component separately.

FIG. 23 illustrates these concepts for the case of a transmission received over a single-bounce path, designated multipath arrival A, a direct path, designated multipath arrival B, and a two-bounce path, designated multipath arrival C. The three multipath components are indicated as having steering vectors of amplitude and angle 15 combinations  $A_1 \angle \alpha$ ,  $A_2 \angle \beta$ , and  $A_3 \angle \gamma$ , respectively. The CURE signal recovery system of the invention presents a directivity pattern that assigns a gain and phase to every possible direction of arrival. The gains and phases corresponding to the three multipath components in this example are shown as  $D_1 \angle \phi_1$ ,  $D_2 \angle \phi_2$ , and  $D_3 \angle \phi_3$ . The corresponding recovered signal for the combination of multipath components is derived 20 from signals of the form:

$$y(t) = [A_1 D_1 e^{j(\alpha+\phi_1)} + A_2 D_2 e^{j(\beta+\phi_2)} + A_3 D_3 e^{j(\gamma+\phi_3)}] s(t).$$

Because the coherent multipath components of each output port's desired signal are optimally phased, weighted, and combined in the recovery process, the CURE method realizes a diversity gain in the presence of multipath in addition to 25 eliminating cochannel interference. The amount of the gain depends on the number and strengths of the distinct multipaths that are combined.

### 9.2 Performance Against Noncoherent Multipath:

Multipath arrivals of a source signal are not always coherent and capable of being combined. The coherency requirement for CURE is that the multipath components of a signal must have high cross-correlation computed over the duration of a processing block or data collection interval. Multipath coherency can be destroyed by large path delay differences and large Doppler shift. When this happens (i.e., when the multipath arrivals are noncoherent), the CURE algorithms recognize and treat the arrivals as independent cochannel signals. The steering vector is estimated for each arrival, and each arrival is separately recovered and assigned to a different output port.

10 Thus, multiple recovered versions of the source signal are formed. It is straightforward to recognize a noncoherent multipath situation because the same signal will be coming out of two or more output ports, each with a slightly different time delay or frequency offset.

FIG. 24 shows the sensor array complex directivity pattern in a situation involving receipt of two coherent multipath components of a desired signal and a non-coherent signal from an interference source. As indicated in the drawing, the complex directivity pattern includes a null presented toward the interference source, while the two multipath components are received and combined in the same way as discussed above with reference to FIG. 23.

20

### 9.3 Performance Against Mixtures of Coherent and Noncoherent Multipath:

In the general case of both coherent and noncoherent multipath, the CURE algorithms automatically partition the multipath arrivals into mutually coherent groups, and determine a generalized steering vector for each group. As in the case of noncoherent multipath, multiple recovered versions of the source signal are formed. The diversity gain is diminished relative to what would have been achieved had the multipath arrivals all belonged to a single coherent group. However, the loss of diversity gain is offset by having multiple replicas of the recovered signal appear at the beamformer's outputs. Moreover, a post-recovery combining gain is possible by adding the signals at the output ports after correction for delay and Doppler shift. If

30

the recovered signals are to be demodulated, this post-recovery combining step would precede demodulation.

FIG. 25 shows the complex directivity pattern formed by the beamformer of the CURE system in a situation similar to that discussed above for FIG. 5 24, except that the desired signal multipath components are non-coherent instead of coherent. The CURE system treats the three arriving signals (the non-coherent multipath components and the interfering signal) as being from separate sources. The directivity pattern shown is the one that would be presented for recovery of the multipath component designated Arrival B. Physical nulls are presented toward the 10 other arriving signals.

FIG. 26 shows a slightly different situation, in which the received signals include a first interferor (A), a second interferor (B) having two coherent multipath components, and a desired signal. Interferor A is rejected by a physical null in the complex directivity pattern. Interferor B is rejected by a generalized null in the 15 directivity pattern, such that the algebraic sum of the multipath arrivals of the signal from Interferor B is zero. If the Interferor B signal arrivals are characterized by gains and phases  $A_1 \angle \alpha$  and  $A_2 \angle \beta$ , and the directivity pattern at the angles of arrival of these components has gains and angles  $D_1 \angle \phi_1$  and  $D_2 \angle \phi_2$ , then the necessary condition for rejection of the Interferor B signals by the generalized null is:

$$20 \quad A_1 D_1 e^{i(\alpha+\phi_1)} + A_2 D_2 e^{i(\beta+\phi_2)} = 0.$$

#### 10.0 Recovering Communication Signals In The Presence Of Interfering Signals:

This section describes how the present invention is used separate and recover signals received in the presence of other interfering signals emanating either 25 from a local "friendly" source or from a deliberately operated jamming transmitter located nearby. The apparatus of the invention includes an antenna array and a cumulant recovery (CURE) processing system, which processes signals received through the antenna array and produces outputs at multiple ports corresponding to the multiple sources from which signals are received at the antenna array. The processing

system converges rapidly on estimates of the desired signals, without knowledge of the geometry of the antenna array.

Two primary problems in this area are addressed by this aspect of the present invention. In one situation, an interfering transmitter may be "friendly," that 5 is to say operated necessarily near a radio receiver, or even on the same ship or vehicle. Even if the transmitter is operating on a different frequency, there is often "spectral spatter" into the receiving band. In a related situation, the interfering transmitter is not "friendly" and is much more powerful than the communication signals to be received and recovered.

10 In the first case, it might be desired to listen and receive while jamming and transmitting simultaneously. Normally such simultaneous transmit and receive operations are not possible, but the friendly transmitter can be selectively turned off to permit reception. Prior to this invention, however, true simultaneous operation of the interfering transmitter and the receiver were often impossible.

15 In the second case, where a strong jamming signal is not under "friendly" control, recovery of the received communication signal requires the use of a nulling antenna array. In the past, systems for recovering a communication signal in the presence of jamming required knowledge of the antenna array geometry and did not always provide rapid convergence on the desired signal solution.]

20 As shown in the drawings, the present invention pertains to systems for recovering communication signals in the presence of interfering or jamming signals, whether or not on the same frequency. More specifically, as shown in FIG. 27, a receiving antenna 280 may be located on the same vehicle or vessel as a local transmitter 282, and there may be a high-powered transmitter 284 located on a nearby 25 friendly vessel operating at the same or a different frequency. A desired signal is received from another transmitter 106, located on land or on another vessel, but is subject to interference from the high-powered transmitter 284 and from the local transmitter 282. In accordance with the invention, the receiving antenna 280 is coupled to a cumulant recovery (CURE) processing system 290, which rapidly processes the 30 signals from the antenna array 280 and generates outputs on multiple ports, effectively

separating the signals received from the high-powered interfering transmitters and the desired received signal onto separate output channels, as indicated for ports #1, #2 and #3.

As shown in FIG. 28, a related situation is one in which reception at the 5 receiving antenna 280 is interfered with by a high-powered jamming transmitter 292, perhaps on an enemy vessel. As in the previous case, the CURE processing system 290 separates and recovers the desired weak signal on one output port (#2), while the jamming signal is isolated and may be discarded from port #1.

#### 10 11.0 Diversity Path Multiple Access (DPMA) Communication:

The blind cochannel signal separation capability of the CURE algorithms can be used to make possible a new communication channel access scheme: Diversity Path Multiple Access (DPMA). This technique enables the design of new communication networks that can accommodate more users simultaneously in a given 15 bandwidth allocation.

The demand for communication services has grown steadily over the past three decades. To a limited extent this demand has been offset by technological improvements that have made new bandwidth available at higher frequencies up to the optical frequency band. Such bandwidth improvements, however, have been unable to 20 keep pace with the growing demand for communication, and new communication methods became necessary. In response, communication system engineers have developed new methods for communication, including networks, control protocols, channel access schemes, and modulation schemes. The principal goal of these developments is to enable more users to use and share a communication resource 25 simultaneously without degrading the quality or creating mutual interference.

##### 11.1 History and Prior Art of Multiple Access Communication:

Prior to this invention, communication engineers had six channel-access schemes at their disposal whereby multiple users in a network could share an RF 30 communication channel in order to transmit simultaneously, more or less, to a central

receiving site (e.g., cell base station or satellite). Communication engineers would use any of the following schemes to enable radio communication between multiple users and a single or multiple base stations. For a wireless network design, a communication engineer would pick one or more of the following methods as the basis for the design.

- 5        • Frequency division multiplexing/multiple access (FDM/FDMA)
- Spatial division multiplexing/multiple access (SDM/SDMA)
- Time division multiplexing/multiple access (TDM/TDMA)
- Code division multiplexing/multiple access (CDM/CDMA)
- Frequency hop multiplexing/multiple access (FHM/FHMA)
- 10      • Angle division multiplexing/multiple access (ADM/ADMA).

Although the terminology in this technology is still evolving, the following distinction is often made. If two transmissions are cooperative, in the sense of being part of a common communication network, the term "multiple access" is used. If the transmissions are independent and not part of a network, the term "multiplexing" 15 is commonly used. The distinction is minor and we shall largely ignore it in this description.

In FDMA, different transmitting users are assigned to different frequencies. More precisely each transmitting user is assigned a different spectral slice that doesn't overlap with those of other users. FDMA was historically the first 20 multiplexing/multiple access method to develop. Its origin is traced back to the beginning of radio, and it is the basis for radio and television broadcast services, whereby an individual is able to receive and select among the signals transmitted by many stations. In an FDMA network, the transmitting users signals are not cochannel, and cochannel interference is thereby avoided.

25        The remaining five channel access schemes enable two or more users to be on the same frequency at the same time (i.e., user transmitted signals can be cochannel). The schemes mitigate or prevent mutual interference by different means.

SDMA is the cellular concept, which originated at Bell Laboratories (*The Bell System Technical Journal*, special issue on Advanced Mobile Phone Service, 30 vol. 58, no. 1, January 1979). Users are divided geographically into cells, seven of

which are indicated at 300 in FIG. 29. Each cell 300 has a base station 302, and the base stations are linked together via fixed land lines 304 or point to point microwave links. A central facility, the mobile telephone switching office (MTSO) 306, controls network operation and generally serves as a gateway for tying the mobile network to other communication services such as the public switched telephone network (PSTN) 308. The set of base stations 302 and the MTSO 306 form the "backbone" infrastructure of the mobile network. Each base station 302 has a finite set of frequencies for sending and receiving, and adjacent cells 300 have different sets of frequencies. Within each cell, FDMA is employed to prevent cochannel interference.

10 There are only a finite number of frequency sets available, and base stations 302 that are separated by some minimum distance use the same frequency sets. Thus, two transmitting users, indicated at 310 that are on the same frequency are necessarily in different cells some distance apart. Each users signal enters the backbone through a different base station. The geographic distance between cells prevents cochannel

15 interference.

SHMA prevents cochannel interference by prohibiting intracell frequency reuse and allowing only intercell frequency reuse. The remaining four channel access schemes TDMA, CDMA, FHMA, and ADMA overcome this restriction and enable frequency reuse among users within a cell-intracell frequency reuse.

20 In TDMA, all users transmit on the same frequency. Each transmitting user is assigned a unique time slot in which to transmit. The average rate of information transmission equals the peak or instantaneous rate times a duty factor which is the slot duration divided by the revisit interval. Although the users are sending at the same time, TDMA prevents cochannel interference because the users do not actually transmit simultaneously.

25 CDMA is a form of direct sequence spread spectrum in which the various users encode their transmissions with orthogonal or nearly orthogonal spreading sequences. All transmitting users use the same frequency. In order to receive a particular signal, a receiver must despread the signal using the same sequence

that was used to spread it at the transmitter. Because of the orthogonality property, the cross-correlation between any two spreading codes is near zero. For this reason, the user signals after reception and despreading are free of cochannel interference. CDMA is the basis of the IS-95 communication standard.

5 FHMA is used to apply frequency hop spread spectrum technology to communication networks. A set of frequency hopping (FH) radios operate in the same band on the same hop frequencies and transmit to a central receiving facility or base station without mutual interference provided the radios use non-interfering hop sequences. Unlike CDMA, the required sequence property is not orthogonality or low 10 cross-correlation, but rather a mathematical relative of the Latin Square. FHMA can be thought of as a dynamic form of FDMA in which the frequency assignments change regularly.

15 ADMA, which is shown in FIG. 30, uses multi-source direction finding (DF) and beamforming technology to isolate and recover the signals from the transmitting cochannel users in a cell. Each base station 302 is equipped with a receiving array connected to an  $N$ -channel receiver (not shown), where  $N$  is the number of antennas in the receive array. The received signals are processed by a multi-source 20 DF system 312 to determine the directions or angles of arrival (DOAs) of the signals on a given frequency. Any multi-source DF algorithm can be used to perform the DF function, such as MUSIC, ESPRIT, or WSF, all of which are well known in the signal processing engineering literature. Each user 310 is characterized by a single unique 25 DOA. Beamforming weight vectors are then computed, as indicated in block 314, from the estimated directions that enable the cochannel signals to be recovered (separated and copied). A transformation matrix, whose rows are the beamforming weight vectors, multiplies the array signals, and the product yields the recovered 30 cochannel signals. Each row of the transformation matrix (i.e., each weight vector) consists of complex numbers that steer the array to one particular signal while putting directional nulls in the directions of the other cochannel signals. The transmitted user signals can be recovered free of cochannel interference provided the users are angularly dispersed such that they have distinct bearing angles measured at the receive array.

ADMA is described in a recent patent by Roy and Ottersten (Richard. H. Roy, III, and Bjorn Ottersten, *Spatial Division Multiple Access Wireless Communication Systems*, U.S. Patent No. 5,515,378, May 7, 1996), but the patent specification uses the term SDMA.

5

### 11.2 A New Method of Multiple Access Communication:

The present invention achieves a new method for channel access in wireless communications that is distinct from the six basic methods described above. The new method is termed diversity path multiple access (DPMA). It overcomes three 10 limitations of ADMA.

First, wireless channels (characterized by their angle spread, delay spread, and Doppler spread) are dominated by multipath. The transmitting user signals arrive at a base station from a multiplicity of directions simultaneously. Angle spread arises due to multipath from local scatterers and remote scatterers. The local scatterers 15 are near the user and near the base station. Measurements have shown that angle spreads for cellular channels generally lie in the range from 2 to 360 degrees. Therefore multipath cannot be ignored, and the idea that a user's signal arrives from a single unique direction is demonstrably not true. The ADMA concept of a single wave arriving from a single direction characterized by a pair of angles for each cochannel 20 signal source is valid in free-space communications, perhaps, but is not valid for wireless communication networks operating in the ultra high frequency (UHF) band in urban, suburban, or rural environments.

Second, most multi-source DF algorithms generally do not work properly or well in a multipath environment. Although well-known techniques such as 25 spatial smoothing and temporal smoothing can be used to DF on the individual multipath components of an arriving signal, the resultant system/processing complexities make such approaches impractical.

Third, even when multipath is absent, ADMA requires the transmitting 30 cochannel users DOAs to be distinct. That is, the angular separation between users cannot be zero. The users must be separated in angle from one another by some

minimum angle. The assignment of a frequency to several cochannel users must take this geometric restriction into account. This limits the utility of ADMA.

The cochannel signal separation capability of the CURE algorithms overcomes the limitations of ADMA. CURE algorithms recover generalized steering vectors as opposed to ordinary steering vectors. An ordinary steering vector is the value of the array manifold at a single angle corresponding to a source's DOA. However, in a multipath environment, the wavefield at the receiving array is composed of more than one plane wave for each source signal. Consequently, sources cannot be characterized unique DOAs or steering vectors.

The CURE signal recovery process is blind to the array manifold. The CURE algorithms find, for each source, a generalized steering vector that corresponds to the sum of all the mutually coherent multipath components of a signal source incident on the array. The generalized steering vector depends on the relative power levels, phases, and ordinary steering vectors of the multipath components. Formally, each generalized steering vector is a complex weighted sum of the array manifold steering vectors at the multipath arrival directions. The complex weights account for path length and attenuation differences among the multipath arrivals. In some cases, the multipath structure consists of a continuum rather than a few discrete components. In such cases the generalized steering vector becomes an integral of the array manifold over all directions. The CURE system determines the generalized steering vectors directly from the received signals, not from the array manifold. Indeed, the various embodiments of the CURE system do not need the array manifold to perform signal separation and recovery.

Once the generalized steering vectors for the cochannel sources have been obtained, it is unnecessary to convert them to source DOAs by using the array manifold, as would generally be done in a system employing DF such as ADMA. Using CURE, the beamforming weight vectors for signal recovery are computed directly from the generalized steering vectors. This is done by one of two methods: (1) projecting each generalized steering vector into the orthogonal complement of subspace or span of the vectors of the other sources; (2) using the minimum variance

distortionless beamformer (MVDR) equations to determine the recovery weight vectors from the generalized steering vectors. These solutions are both well known in the signal processing engineering literature. If the generalized steering vectors are determined perfectly, i.e., no estimation error, then the former solution would provide 5 zero crosstalk (i.e., maximum signal-to-interference ratio) among the recovered signals at the beamformer output. The latter solution would provide recovered signals having maximum signal-to-interference-plus-noise ratio (SINR).

An illustration of how the invention is used in the context of a DPMA communication system is provided in FIG. 31, which shows a single cell 300, with a 10 basestation 302 and two users 310. One user (A) reaches the basestation through multipath propagation, while the other has a direct propagation path to the basestation. A CURE processing system 316 receives and processes the signals received by the basestation 302. In communicating with cochannel user A the system 316 generates a beamformer directivity pattern that presents a physical null toward the other user, but 15 presents a generalized steering vector that results in both multipath components from cochannel user A being received and combined.

A feature of the CURE systems is that the omnipresence of multipath enables the recovery (separation and copy) of signals from sources that have zero angular separation from the point of view of the receiving base station array. For 20 example, consider two sources that are collinear with the base station such that one source lies behind the other. Although the direction to both sources is identical and the ordinary steering vectors for line of sight propagation are identical, the multipath configurations are entirely different. Therefore, the generalized steering vectors of the two sources will be entirely different. This facilitates the separation and recovery of 25 the cochannel source signals in situations where ADMA cannot work.

Because the coherent multipath components are optimally phased, weighted, and combined in the recovery process, the CURE method realizes a diversity gain in the presence of multipath. The amount of the gain depends on the number of distinct multipaths that are sufficiently coherent to be able to be combined.

Not all multipath components of a source will be coherent and capable of being combined. The coherency requirement is that the multipath components of a signal must have high cross-correlation computed over the duration of a processing block or data collection interval. Multipath coherency can be destroyed by large path 5 delay differences and large Doppler shift. When the multipath components of a signal source are not all mutually coherent, the CURE algorithms automatically partition the multipath arrivals into coherent groupings, and determine a generalized steering vector for each group. When this happens, multiple recovered versions of the source signal are formed. The diversity gain is diminished relative to what would have been 10 achieved had the multipath arrivals all belonged to a single coherent group. However, the loss of diversity gain is offset by having multiple replicas of the recovered signal appear at the beamformer's outputs.

By using the multipath combining feature of the CURE algorithms, a new communication network channel access method is achieved: DPMA. In DPMA, 15 the communication path that defines the link from a transmitting user to a receiving base station consists of a weighted combination of multipaths. The multipath processing capability of the CURE systems provide a practical means for implementing a communication network employing DPMA. The CURE algorithms determine the complex multipath-combining weights of a desired signal automatically, dynamically, 20 and in real time, while rejecting the multipaths of cochannel other-user signals.

It is important to note the difference between DPMA and ADMA. The orthodox ADMA concept consists of a single wave arriving from a single direction for each signal source (i.e., a multipath-free environment). A direction-finding algorithm is employed to estimate the direction parameter associated with each arriving cochannel 25 signal. Under this model, two signals are inseparable if their directions of arrival are identical (i.e., if the sources are collinear with the receive array). DPMA by contrast operates in a signal environment where multipath is a key feature. DPMA, unlike ADMA, is tolerant with regard to angular separation between sources. Even collinear sources having zero angular separation at the receiving array are separable because

different multipath structures cause the sources to have different generalized steering vectors which the CURE algorithms exploit.

### 12.0 Application To Two-Way Mobile Wireless Communication Systems:

5        The CURE cochannel signal separation technology is applicable to communication networks composed of two-way communication links in which multiple transmissions occur simultaneously on the same frequency. The natural application for CURE is to the receiving end of a communication link provided it is practical to have an antenna array at the receiving end. For a two-way communication link, this would  
10      10 mean having a receiving antenna array at both ends of the link. In many situations, however, it is practical to have an array at only one end of a communication link. For instance, in personal mobile wireless communication networks, it is impractical to have an array built into the user's portable handheld units. In such situations, it is possible, under certain conditions, to establish and maintain isolation between different  
15      15 cochannel users by putting arrays at just one end of the communication link.

      CURE cochannel signal separation technology can be applied to cellular communication systems in which the earth's surface is partitioned into localized regions called 'cells,' as described above with reference to FIG. 29. Examples of cellular personal mobile wireless communication systems are the Advanced Mobile Phone System (AMPS) and Global System Mobile (GSM). (See *The Bell System Technical Journal*, special issue on Advanced Mobile Phone Service, vol. 58, no. 1, January 1979.)

      The CURE cochannel system has been described to this point as a technology used at the receiving ends of communication links provided the receiving  
25      25 ends have multi-element antenna arrays. In the case of cellular networks, however, economics dictates that arrays be put at base stations only. There are two reasons for this:

- An antenna array is a large and expensive physical asset, best suited to installation at fixed base stations where proper maintenance and repair is

possible. Mobile units would be larger and more expensive if they were required to have antenna arrays built in.

- A single base station array can serve many users at once. Since each cell has more mobile units than base stations, total system cost is lower if arrays are employed at the base stations only.

5 The effect of locating arrays at base stations is to lower the initial equipment purchase cost to the subscribers while increasing the infrastructure cost, which is spread over all subscribers in the form of monthly service charge.

Like the application to cellular networks, CURE cochannel signal 10 separation technology can be applied to satellite-based personal communication networks in which a space-based array on a satellite forms spot beams on the surface of the earth that define regions similar to the cells formed with terrestrial base stations. All communication within a spot beam is between the mobile users and the satellite. Communication that bypasses the satellite, between two users in the same spot beam, is 15 precluded. Examples of satellite-based personal mobile wireless communication systems are Iridium, Odyssey, and Global Star.

There are several reasons and advantages relative to the use of CURE cochannel signal separation technology in personal mobile wireless communication networks.

20

- The capacity of a network to accommodate users can be increased by employing intra-cell frequency reuse. CURE technology makes this possible by means of diversity path multiple access (DPMA) on the *reverse* links or *uplinks* from mobile user-to-base stations or satellite and by transmit beamforming on the *forward* links or *downlinks* from base station or satellite to mobile user.
- Apart from capacity improvement, CURE provides diversity gain which, when used with suitable power control algorithms, can enable the mobile users to maintain reliable communication with less average transmitted power.

- CURE provides general interference immunity not only from other users in the network but from arbitrary radiated interference, whether deliberate or unintentional.

5 12.1 Transmit Beamforming:

The selectivity that enables several users to simultaneously share a radio-frequency (RF) channel for transmission can be accomplished by beamforming at the transmitters instead of at the receivers. In the case of a cellular network, it is possible, by means of transmit beamforming, for forward link transmissions (from base 10 station to mobile user) to be sent out with directivity patterns that reach the intended user while preventing reception at other cochannel users. Two methods can be used to accomplish the requisite transmit beamforming function: switched fixed beams and adaptive beams. The basic principles of both approaches are known in communication engineering. However, proper operation depends on integration with the receive 15 beamforming function provided by the CURE system. This integration is described below.

In the switched beam approach, a transmit antenna array and a set of fixed pre-formed beams is available for transmission. The beams are formed by applying signals with appropriate gains and phases to the antennas. The gains and 20 phases can be created either by a passive beamforming matrix that is inserted into the signal path ahead of the antenna array. The outputs of the beamforming matrices are then summed in power combiners that drive each array antenna. The preferred approach, shown in FIG. 32, eliminates the expense of RF hardware beamformers in favor of digital signal processing. In this method, a signal to be transmitted to a user is 25 input on one of  $N$  multiple lines 320 to one of  $N$  sets of multipliers 322. Each set of multipliers has as other inputs a transmit beamformer weight vector, which is derived from a transmit/receive beamformer weight vector computer 324. The latter computer receives estimated generalized steering vectors on lines 36 from the CURE system and generates receive beamformer weights on lines 48 (see FIG. 4A), and transmit 30 beamformer weight vectors on lines 326.

Thus, in each set of multipliers 322, a signal to be transmitted to a user is multiplied by a transmit beamformer weight vector, which is an  $M$ -dimensional complex weight vector, where  $M$  is the number of antenna elements. For each of  $N$  users, the outputs of the multipliers 322 are summed in a plurality  $M$  of summers 328.

5 That is to say, each summer 328 sums the contributions of multiple user signals associated with a particular antenna element. The signal to be radiated by the  $i^{\text{th}}$  antenna of  $M$  elements is the sum of  $N$  terms, each being a complex weighted version of the signal to a different user. An  $M$ -channel digital-to-analog converter (DAC) 330 and linear power amplifier (LPA) 332 is used to drive each antenna. This latter

10 method does not require expensive analog rf beamforming matrices and power combiner hardware, since the multipliers 322 and summers 328 are digital processing components, as indicated by the envelope 334.

In the switched beam approach, the beamforming weight vectors are pre-computed and stored in memory. Each weight vector can be used to create a

15 directional beam that puts transmitted energy in a different direction. The set of all such weight vectors provides a family of pencil beams that covers all directions in the cell. Only one such beam is selected for transmission on each of the  $L$  forward links. The method of selection is described below. The method mitigates, but does not eliminate, cochannel interference because the energy of a signal unintentionally

20 radiated to other cochannel users is suppressed to the sidelobe level of the beam, assuming the other users do not fall into the main lobe of the beam. For cellular systems that use analog frequency modulation (FM) on the forward links like the AMPS system in the United States, there is, in addition to sidelobe suppression, the signal capture effect of FM discriminators that provides additional suppression of

25 unwanted cochannel interference.

A beam is chosen for transmission to a particular user by means of logical rules embodied in a beam selection algorithm. The objective is to prevent energy from reaching the other cochannel users where it would interfere with the intended signals being sent to those users. Consider the following set of assumptions,

30 reasonable for many wireless communication services that operate at UHF frequencies:

- The base station has separate transmit and receive arrays.
- The transmit and receive arrays are geometrically similar (i.e., have the same shape).
- The transmit and receive arrays have the same size-frequency products (i.e., the ratio of the transmit-to-receive array sizes equals the ratio of the receive-to-transmit frequencies).
- The transmit and receive arrays are mounted on a common vertical mast.
- The dominant multipath scatterers are not in the immediate vicinity of the arrays, so that the arrays are in the farfield of reradiation from scatterers, and the elevation or depression angle of arrival is essentially zero at both arrays.

Under these assumptions, the best beam for sending energy to a given user is the one whose beamforming vector is most nearly orthogonal to the generalized steering vectors of the other cochannel users (the generalized steering vectors being those derived from reception of the reverse link signals at the base station). Orthogonality between two vectors is strictly defined as an inner product of zero. However, strict orthogonality is not generally possible. Fortunately, it is often good enough to pick the beam whose weight vector has the smallest inner product with the reverse link generalized steering vectors of the other cochannel users. This beam will radiate minimal sidelobe energy to the other users.

The beam selection criterion for using a fixed switched-beam array can be stated precisely: Choose the beam that maximizes the ratio of the inner product of the beam vector with the generalized steering vector of the intended user divided by the sum of the inner products with the generalized steering vectors of the unintended cochannel users.

The method just described uses a fully adaptive array for the reverse link receive function, as implemented by the CURE method, together with a switched-beam array for the forward link transmit function. The key feature of this approach is that antenna arrays are employed only at base stations.

A somewhat different approach would be to perform the transmit beamforming by using the exact generalized steering vectors as are derived by the receive function. This method requires a transmit array that is geometrically similar to the receive array as described above (i.e., the transmit and receive arrays have the 5 same shape but are scaled by the ratio of the receive-to-transmit frequencies). For example, in the case of the AMPS analog cellular systems, the transmit and receive frequencies are offset by 45 MHz. Because the total system bandwidth is small compared to the operating frequencies, the 45 MHz offset can be regarded approximately as a 5 percent difference in scale. By using a scaled transmit array, if a 10 generalized steering vector obtained by CURE on receive is used for transmit, then the same array directivity pattern will result. Thus, lobes and nulls will be placed at the same angles. Nulls directed to other cochannel users on receive will also be directed at the same other users on transmit, thereby enabling the base station to selectively direct a signal at a particular desired cochannel user.

15 In a multipath environment, the desired user and other user signals will generally be via diversity paths (i.e., the DPMA concept). In this case, the generalized steering vectors derived by CURE on receive cause the receive array (and hence the transmit array) to have a complex directivity pattern for each user that sums the multipath arrivals of the desired signal with complex weights (gains and phases) that 20 causes them to add in phase, while simultaneously summing the multipath arrivals of each other user cochannel signal with complex weights that causes these signals to sum to zero. Thus, other users are rejected by generalized nulls or orthogonality rather than by physical nulls at specific angles. The energy transmitted to a particular user will be sent in the same direction as the receive multipath components, with the same 25 phase and gain relationships. Therefore, the signal will reach the intended user with a substantial signal level via the diversity path. Simultaneously, the signal will reach the other users via multiple paths that will sum to zero provided the mobile users are using a simple omnidirectional antenna for both transmit and receive.

FIG. 33 is block diagram of a transmitter for use in one form of the 30 CURE system. Some of the components of the transmitter have already been

introduced in the discussion of FIG. 32. A transmit weight vector computation or beam selection module 340 generates on lines 326 a transmit weight vector for each user  $k$ . the module 340 generates the transmit weight vector based on either of the two approaches discussed above An information signal to be transmitted to user  $k$  is 5 modulated in a modulator 342 and then multiplied by the transmit weight vector for user  $k$ , in a set of multipliers 328. The portion of the transmitter including the modulator 342 and multipliers 322 is referred to as the transmit beamformer 344. Next the outputs of the multipliers 322 are summed in a set of  $M$  summers 328, each summer receiving as inputs an antenna element contribution associated with each of the 10 users. Thus each summer 322 has  $N$  inputs if there are  $N$  users. The summers 328 are collectively referred to as a signal combiner 346.

The outputs of the summers 328 are then processed in what is referred to as the air interface 348 of the transmitter. The air interface includes a set of complex digital-to-analog converters (DACs), each of which produces two outputs, the in-phase 15 and quadrature components of the complex signals. These complex signal components are multiplied by a carrier signal in additional pairs of multipliers. More specifically, each complex output pair from a complex DAC 330 is multiplied by signals proportional to  $\cos \omega_c t$  and  $\sin \omega_c t$ , respectively, where  $\omega_c$  is the angular carrier frequency. The resulting products in each pair are then added in summers 352 and 20 coupled to one of the linear power amplifiers 332, and from there the signals are coupled to an antenna element 110.

### 13.0 System For Separating And Recovering Multimode Radio Signals:

This section describes a method and apparatus for mitigating 25 polarization effects on propagated radio signals. In the case of dual-polarized radio transmissions, the effects of a polarization-changing propagation medium are avoided by separating the two received signals without regard to their polarization states.

This invention relates generally to radio communications and, more 30 specifically, to problems that arise, due to natural propagation conditions, when multiple cochannel signals of practically the same frequency are received at

approximately the same time. Propagation conditions may cause unwanted polarization mixing of the signals. Separating and recovering the original signals poses difficulties in receiver design.

A related problem is multipath propagation caused by reflections from atmospheric layers, such as the D-layer, E-layer or F-layer. The problem manifests itself as frequency selective fading or phase distortion that limits the communication capability of high-frequency (HF) signals. As already discussed above in Section 9.0, the CURE system handles multipath components advantageously by combining all coherent signals arriving over different paths as a result of reflections from buildings in an urban environment. Multipath propagation effects caused by atmospheric reflections are handled in exactly the same manner.

In some communication systems electromagnetic propagating waves are used to carry two independent information signals on different polarizations of the same carrier signal. These polarizations need not be orthogonal, but do need to be linearly independent relative to two orthogonal "basis" polarizations, e.g. vertical and horizontal linear polarizations or left-hand circular and right-hand circular polarization. A traditional problem is that the polarization of a transmitted signal is changed by the propagation medium so that the signal arrives at the receiving antenna with a different polarization from the one in which it was transmitted. The polarization change may be due to reflection from oblique surfaces, refraction, or the phenomenon of Faraday rotation. Conventional receivers separate differently polarized signals because each receiver has knowledge of the expected polarization states. When the polarization of one or both signals is changed during propagation, the conventional receiver is incapable of properly separating the two signals.

The present invention separates the received signals without regard to their possibly changed polarization states. If only one signal is received with an unknown polarization is received at a dual-polarized antenna, the invention can extract the signal and determine its polarization state. If two signals are sent on orthogonal polarizations, the signal polarizations can be random and not orthogonal at the receiving site, making reception of either signal subject to cochannel interference from

the other signal. CURE processing solves the problem by separating and recovering up to two independent signals arriving at the receiving array with differently polarizations, provided only that the polarizations are linearly independent (i.e., not identical). The key advantage of the invention in this application is that it is "blind" to the polarization 5 states of the received signals. Prior knowledge of the polarization state is not needed to separate and recover the signals. In addition, the CURE approach is fast enough to enable the recovery of signals whose polarization is time-varying.

As shown in FIGS. 34A and 34B, one type of communication system makes use of dual-polarized signals at the same frequency. For example, transmitters 10 360A and 360B transmit uplink signals A and B to a communication satellite 362, which retransmits the signals, with different polarization states, to a dual-polarized antenna 364 on the ground at a receiving site. However, an atmospheric layer 366 causes polarization mixing of the two signals, which arrive at the receiving antenna with scrambled polarization states. The received signals are processed by a CURE 15 processing system 368, which effectively separates out the signals A and B without regard to their scrambled polarization states. Because of the CURE processing system 368 is "blind" to antenna configuration, and to the polarization state of the received signals, separation and recovery of signals A and B can be effected even when both have their polarization states altered during propagation from the satellite transmitter.

20

#### 14.0 Application to Separation of Signals Transmitted Over "Waveguide":

This section describes a method and apparatus for separating and recovering signals transmitted onto a "waveguide." As mentioned earlier, the term "waveguide" as used in this specification is intended to include any bounded 25 transmission medium, such as a waveguide operating at microwave frequencies, an optical fiber operating at , a coaxial cable, or even twisted-pair conductors operating at lower frequencies. Regardless of the waveguide medium, the signals are received at an array of sensor probes installed in the waveguide, and are fed to a cumulant recovery (CURE) system that separates and recovers the original signals without regard to how

the original propagation modes may have become scrambled as a result of transmission along the waveguide.

5 Waveguides and optical fibers are widely used for the transmission of multiple independent cochannel signals simultaneously, by using a different propagating mode for each signal. However, due to kinks, bends and surface and refractive irregularities in the waveguide or fiber, a phenomenon called mode conversion occurs, and the propagated energy is converted from one mode to another during propagation along the waveguide or optical fiber medium. Over a long distance of propagation, the signals tend to become scrambled across the propagating modes.

10 A well known approach to conserving bandwidth is to employ different propagating modes for different signals of the same frequency, and to rely on the different propagating modes to effect separation of the signals at the receiving end of the waveguide or optical fiber. Unfortunately, however, mode conversion often occurs, especially in long waveguides or fibers, as a result of kinks, bends, and surface and 15 refractive irregularities of the propagation medium. The modes become scrambled and separation at the receiving end becomes difficult. For optical systems, these difficulties are somewhat reduced by the use of expensive single-mode fiber.

20 FIG. 35 shows, by way of example, a computer network employing an optical fiber 370 and having a plurality of computer workstations 372 connected to the fiber by couplers 104, each of which couples a workstation to the fiber using a different propagation mode, but at the same optical frequency. In accordance with the invention, a plurality of probes 376 are also coupled to the fiber 370, providing three 25 output signal lines for connection to a cumulant recovery (CURE) processing system 378, which generates separated signals A, B and C at its signal recovery ports.

25

### 15.0 Application to Radio Direction Finding:

This section describes a method and apparatus for finding accurate directions of multiple radio signal sources without the need for a fully calibrated antenna array. Signals from the antenna array are processed in a cumulant recovery 30 (CURE) processing system to recover the signals and obtain estimated steering vectors

for the multiple sources. Signals from a subarray of antennas that are calibrated are combined with the steering vector estimates to obtain accurate directional locations for all of the sources. There need be only as few as two calibrated antenna elements in the subarray.

5 This invention relates generally to direction finding (DF) systems and, more particularly, to DF systems using arrays of radio antennas. Traditional super-resolution direction finding systems require an array of  $N+1$  calibrated antennas and receiving channels to resolve  $N$  source locations (directions). Maintaining large arrays of antennas in calibration adds to the cost of the system. Moreover, traditional DF  
10 systems do not always converge rapidly on the direction solutions.

FIG. 36 shows a direction finding system in accordance with the invention, including an array of antennas 380, only two of which are calibrated, a CURE processing system 382 and a copy-aided direction finding system 384. Signals are received from multiple sources 386 at different directional locations with respect to  
15 the antenna array 380. As described in detail in the foregoing descriptive sections, the CURE processing system 382 separates and recovers the signals from the sources 386 and outputs the recovered signals from separate output ports, as indicated at 388. A by-product of the signal recovery process is a set of steering vector estimates for the multiple sources 386.

20 Assume that the  $k^{\text{th}}$  port provides the steering vector estimate  $a_k(m)$  from its analysis of the  $m^{\text{th}}$  block of data "snapshots," and the steering vector from the calibration table for the bearing  $\theta$  is denoted as  $a(\theta)$ . When an antenna array is "calibrated," a calibration table is generated, associating every bearing angle with an antenna steering vector. The dimensionality of  $a(\theta)$  is equal to the number of calibrated  
25 sensors, which must be greater than or equal to two. After the steering vectors are estimated, a search is done to estimate the directions of arrival for the sources captured by the ports.

The bearing  $\theta_k$  of the source captured by the port  $k$  is estimated by the maximizer of the DOA spectrum:

$$\theta_k = \operatorname{argmax}_{\theta} \frac{|\mathbf{a}_k^H(m)\mathbf{a}(\theta)|}{\|\mathbf{a}_k(m)\| \|\mathbf{a}(\theta)\|}.$$

Some alternative methods to that just described were given by B. Agee in "The Copy/DF Approach to Signal Specific Emitter Location," Proc. Twenty-Fifth Asilomar Conference on Signals, Systems, and Computers, pp. 994-999, Pacific Grove, CA, November 1991. Agee concludes that the copy-aided DF method gives more accurate DOA estimates than other systems, such as MUSIC (discussed at length in the Background of the Invention section), and that these estimates require less computation than does MUSIC. An additional advantage is that only two calibrated sensors are adequate for azimuth estimation since the search is performed using the estimated steering vector for one source instead of the signal subspace. In the case of multipath propagation, more sources can be resolved by the copy-aided DF approach than by MUSIC when spatial smoothing is used.

#### 16.0 Application to Extending the Dynamic Range of Receiving Systems:

15 This section describes a method and apparatus for extending the effective dynamic range of a radio receiving system by removing the principle products of distortion through the use of a cumulant recovery processing system. A received signal of interest is separated from the products of distortion, which are independent of the signal of interest. The signal is forwarded for further processing and the products 20 of distortion are discarded, resulting in an extended dynamic range.

The dynamic range is a measure of the useful output of a receiver in relation to noise and other unwanted components. It is limited by the intermodulation and distortion products that result from analog and digital nonlinearities. Analog nonlinear distortion products or spurs can be generated due to signal overload or 25 saturation of the first stage, mixer noise, and other sources. Digital systems employ analog-to-digital (A/D) converters that produce nonlinear distortion due to uniform quantization noise, A/D saturation, non-monotonicity of the A/D characteristic, sampler aperture jitter, and other physical effects. Accordingly, there has been an ongoing need for significant improvement in the dynamic range of a receiver system.

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FIG. 37 shows a multichannel receiver 390, receiving signals from sources 392 through an antenna array 393 and coupling the input signals to a cumulant recovery (CURE) processing system 394. The received signals, after analog processing and analog-to-digital conversion, have a spectrum that includes a number of products 5 of distortion, in the form of nonlinear spurs in the spectrum, as well as lower-level quantization noise across the entire spectrum of interest. The effect of CURE processing is to separate and recover (or discard) received signals. In this case, the CURE processing system provides an output port for the desired signal, and generates other outputs corresponding to the principal products of distortion, which may be 10 discarded. The resulting spectrum after CURE processing exhibits improved effective dynamic range, and contains only lower intensity spurs, and low level noise. Accordingly, the invention eliminates a number of distortion products in the receiver output and provides a desired output signal with fewer and lesser products of distortion.

15

#### 17.0 Application to High Density Recording:

This section describes a method and apparatus for separating and recovering data recorded on closely spaced tracks on a recording medium. An array of sensors senses recorded data from multiple tracks simultaneously, and a cumulant 20 recovery processing system separates and recovers the data from each of the multiple tracks, without crosstalk or mutual interference. Use of the invention permits recording of data at much higher densities than is conventional, so that more data can be stored on a recording disk without increasing its physical size.

For space efficiency, magnetic recordings use multiple parallel tracks to 25 record information. Both rotating disks and linear tape use parallel tracks. Tracks can be laid down in the recording medium side-by-side on the surface and on top of one another at different vertical depths. On playback, a playback head attempts to sense individual tracks without crosstalk or interference from adjacent tracks, but at sufficiently high recording densities and small track sizes, crosstalk becomes a 30 significant problem. Accordingly, designers of such systems are constantly seeking to

improve playback head performance and the precision with which the playback head can be positioned to read information from each track. The present invention provides for increased recording density without crosstalk or mutual interference between adjacent tracks.

5 As shown in FIG. 38, which depicts a recording disk 400 by way of example, playback or retrieval of recorded information is effected by means of a multisensor array 402, which has individual sensor elements that can sense recorded information on more than one track simultaneously. In general,  $N$  sensors will permit separation of information from  $N$  adjacent tracks. In the illustrated form of the  
10 invention, there are three sensors in the array 402 and the array spans across three adjacent recording tracks. The signals from the three sensors are processed as independent cochannel signals by a cumulant recovery (CURE) processing system 404, which generates outputs on three ports, corresponding to the signals on the three tracks over which the sensor array is positioned. Depending on the design of the system,  
15 selection from among the three outputs may be simply a matter of choosing the strongest signal, which should correspond to the track above which the array is centered, or utilizing the information in all three tracks, based on identifying data contained on the tracks themselves. Accordingly, the invention represents a significant improvement in recording and playback techniques using high-density recording media.

20

### 18.0 Application to Complex Phase Equalization:

This section describes a method and apparatus for effecting automatic phase rotation equalization of a quadrature amplitude modulated (QAM) signal received from a transmitter. Because QAM signals are subject to an unknown phase rotation  
25 during propagation, de-rotation or phase rotation equalization is required before the received signal can be QAM demodulated. In this invention, received downconverted QAM signals are subject to processing in a cumulant recovery (CURE) processing system, which recovers the originally transmitted I and Q signals and automatically provides phase rotation equalization, without knowledge of the amount of rotation.

Thus the invention provides the correct amount of phase compensation automatically, even as channel propagation conditions change.

This invention relates generally to communication systems and, more particularly, to phase rotation equalization in communication systems. Many 5 communication systems use a form of modulation referred to as quadrature amplitude modulation (QAM) for transmitting digital data. In QAM, the instantaneous phase and amplitude of a carrier signal represents a selected data state. For example, 16-ary QAM has sixteen distinct phase-amplitude combinations, which may be represented in a "signal constellation" diagram as sixteen points arranged on a square matrix. A 10 special case of QAM signals is the phase-shift keyed (PSK) signals for which the instantaneous phase alone represents a selected state. For example, 16-PSK has sixteen distinct phase selections, and can be represented as sixteen equally spaced points on the unit circle.

Transmission of the modulated signal causes an unknown phase rotation 15 of the signals, and phase rotation correction, or equalization, is required at the receiver before the QAM signals can be demodulated. The present invention provides a convenient and automatic approach to effecting this phase rotation equalization. FIG. 39 shows a conventional transmitter, including a QAM modulator 410 and a transmitter 412. At the point of transmission, the signal constellation diagram is as shown at 414, 20 with sixteen phase-modulus points arranged in a square matrix. Each point on the diagram represents a unique data state. At the receiver site, a receiver and downconverter 416 generates I and Q signal components. The signal constellation diagram corresponding to these signals is as shown at 418. The constellation has been rotated and must be corrected before QAM demodulation can take place. The receiver 25 site also has a cumulant recovery (CURE) processing system 420 installed between the receiver/downconverter 416 and a QAM demodulator 422. As will be further explained, CURE processing has the effect of compensating for the phase rotation induced during propagation of the signal to the receiver site, as indicated by the phase-corrected QAM signal constellation at 424.

The in-phase and quadrature components (I and Q) of a digital communication signal are independent and identically distributed at the transmitter output, as indicated in FIG. 40Aa). If  $x(t)$  is the original communication signal (in analytic representation) with in-phase component  $x_p(t)$  and quadrature component  $x_q(t)$ , respectively, then  $x_p(t)$  and  $x_q(t)$  are statistically independent. After transmission, the channel distorts the transmitted signal and the receiver recovers it with gain and phase ambiguity (ignoring measurement noise), i.e. if  $y(t)$  is the output of the receiver, we have:

$$y(t) = G \exp(j\theta) \cdot x(t).$$

If  $y_p(t)$  and  $y_q(t)$  denote the in-phase and quadrature components of  $y(t)$  respectively, then we can write:

$$\begin{bmatrix} y_p(t) \\ y_q(t) \end{bmatrix} = G \cdot \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_q(t) \end{bmatrix}.$$

The gain term  $G$  is real-valued and affects only the scale of the signal constellation, but not the constellation's shape or alignment with the I and Q axes. Therefore, without loss of generality, we may assume that  $G=1$ .

The effect of transmission is to rotate the entire signal constellation by the unknown phase angle  $\theta$ , as is shown in FIG. 40B. In order to demodulate the signal correctly, the constellation must be "de-rotated" back to its original position prior to demodulation. This de-rotation operation must be accomplished by complex phase equalization or phase correction of the I and Q signals, which compensates for the distortion introduced by the communication channel and the lack of phase reference in the receiver downconverter's local oscillator.

The CURE method can be applied to provide a unique solution to the problem of complex phase rotation equalization. The signal's center frequency for downconversion must be known accurately enough so rotation does not occur during a processing block. The following two paragraphs help explain how the CURE system effects complex phase correction:

1)  $y_p(t)$  and  $y_q(t)$  are not independent but are uncorrelated. The absence of statistical independence is evident by inspection of FIG. 40B. Uncorrelatedness is

implied by the equation. Because the signals are uncorrelated, second-order statistics such as cross-correlation functions provide no information to correct for the rotation of the signal constellation.

2) The rotation correction problem can be considered as a blind signal separation problem in which there are two sensor signals  $y_p(t)$  and  $y_q(t)$ , each of which is a linear combination of two independent source signals  $x_p(t)$  and  $x_q(t)$ . This is precisely a problem model to which the CURE processing system can be applied. By applying the CURE method to the components of the analytic signal, the vector channel is phase equalized, the original independent I and Q signals are recovered, and the received signal constellation is de-rotated. In addition, since  $y_p(t)$  and  $y_q(t)$  are uncorrelated, the covariance matrix used in the CURE system will be a scaled identity matrix, which simplifies the preprocessing required in the CURE system.

The principal advantage of using the CURE system as an equalization technique is that the rotation angle  $\theta$  need not be known. The CURE system compensates for the angle automatically to provide independent output signals. Moreover, the equalization process adapts as channel conditions change.

The CURE system can be used to adjust the complex phase for single-dimensional constellations, such as pulse-amplitude modulation (PAM). In this case, the scenario can be considered as a two-sensor, single-source, signal enhancement problem, which can be handled by the CURE processing system.

#### 19.0 Extension to Wideband Signal Separation:

The present invention is fundamentally a method for separating and recovering narrowband cochannel signals illuminating a sensorarray. However, it is possible to extend the method to the separation and recovery of wideband signals. This is accomplished by:

- 1) Partitioning the wideband spectrum into multiple narrowband segments.
- 2) Using an array of cochannel processors to perform signal separation in each narrowband segment.

3) Combining the narrowband results to recover the original wideband source waveforms.

Steps 1 and 2 are straightforward. Step 3, however, is intricate and requires a special cumulant test to associate the ports at one frequency segment with the 5 ports at adjacent frequency segments. Methods to accomplish these steps are described below. The overall method is capable of separating and reconstructing wideband signals with no special constraints on the signals or their spectra other than that the components of the signals in each narrowband segment must be non-Gaussian. A key advantage of this method is that the signal spectra are not required to be gap-free (i.e., 10 have a convex support set).

### 19.1 Partitioning Wideband Measurements to Narrowbands:

To apply the CURE algorithm to separate the signals, it is necessary to decompose the sensor measurements into narrowband components. This decomposition 15 step is depicted in block 430 of FIG. 41. If  $\mathbf{r}(t)$  is the array snapshot at time  $t$ , then let  $\mathbf{r}(t,f)$  denote the measurement component filtered by a bandpass filter centered at frequency  $f$ . The bandpass filters are designed to satisfy the expression:

$$\mathbf{r}(t) = \sum_{f=f_l}^{f_u} \mathbf{r}(t,f).$$

where  $f_l < f < f_u$  is the wideband analysis spectrum. With this analysis approach, the 20 signal model for each band is expressed as

$$\mathbf{r}(t,f) = \mathbf{A}(f)\mathbf{s}(t,f) + \mathbf{n}(t,f).$$

The following important fact about the cross-cumulants of bandpass filtered signals will be exploited in order to associate the ports of different signal separation processors operating in different frequency bands:

$$25 \quad \text{cum}(s_k(t, f_1), s_k^*(t, f_1), s_l(t, f_2), s_l^*(t, f_2)) = \gamma_{4,k}(f_1, f_2) \delta_{k,l},$$

where  $\gamma_{4,k}(f_1, f_2) \neq 0$  in general, and  $\delta_{k,l}$  is the Kronecker delta function

$$\delta_{k,l} = \begin{cases} 1 & \text{if } k = l \\ 0 & \text{otherwise} \end{cases}$$

In other words, the cross-cumulant is nonzero for different frequency components from the same source and zero for different sources.

This property is in contrast to the cross-correlation between the components of signals at different frequencies which, except for signals that exhibit 5 second-order cyclostationarity, is generally given by

$$E \{ s_k(t, f_1) s_l(t, f_2) \} = \sigma_k^2(f_1) \delta_{k,l} \delta_{f_1, f_2}.$$

Here, we see that the components of a given signal at different frequency bands are uncorrelated and the components of different signals are uncorrelated.

10 The advantage of the cumulant property noted above is that it provides a method (described below) for associating the narrowband parts of a wideband signal that is broadly applicable to all signal types regardless of whether a given signal exhibits 2nd-order cyclostationarity.

### 15 19.2 Signal Separation in Narrowbands:

Each narrowband component ( $r(t, f)$ ) is fed to a different CURE signal separation processor 432 that separates and recovers the signals that comprise the narrowband component.

Let  $gk(t, f)$  be the waveform recovered by the  $k^{\text{th}}$  port of the CURE 20 subsystem that operates in band  $f$  processing  $r(t, f)$ . We shall show a method of determining which narrowband port signals are part of a common wideband signal, and how to combine these port signals in order to reconstruct and recover the wideband signal.

### 25 19.3 Combining Narrowbands:

The problem of combining the recovered narrowband signals to form wideband signals is complicated primarily by the fact that the ports for different bands capture different sources. The combining step is indicated as block 434 in FIG. 41. In general,

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$$\hat{s}_k(t) \neq \sum_{f=f_i}^{f_i} g_k(t, f).$$

Consider first the case in which the wideband analysis band is broken into two narrow bands  $f_1, f_2$ , and two processors, each equipped with  $L$  signal extraction ports to independently process the bands.

5 Suppose the first port of the processor operating in band  $f_1$  has captured a signal and we wish to find whether some port of a second processor assigned to a different band  $f_2$  captures the same signal. This determination is made by the following test. Compute the following quantity for the active ports (indexed by  $l$ ) of the second processor:

10

$$d(f_1, l; f_2, l) = \frac{E \{ |g_1(t, f_1)|^2 \} E \{ |g_l(t, f_2)|^2 \}}{|\text{cum}(g_1(t, f_1), g_1^*(t, f_1), g_l(t, f_2), g_l^*(t, f_2))|}.$$

15

We associate a port of the second processor to the first port of the first processor if both ports jointly minimize the quantity and if the minimum is below a threshold. The threshold is set to limit the number of false association decisions on average. For example, if port 3 of the second processor provides a minimum below threshold, then the waveforms from the two processors would be combined according to

$$\hat{s}_1(t) = g_1(t, f_1) + g_3(t, f_2).$$

Conversely, if the maximum is below threshold, then we let

$$\hat{s}_1(t) = g_1(t, f_1).$$

20

In the general case, there are  $J$  signal separation processors operating in  $J$  bands, each having active signal energy on up to  $L$  output ports. The method of band association in the general case is to first compute the "distance" between all pairs of ports by computing the pseudo-metric:

$$d(i, k; j, l) = \frac{E \{ |g_k(t, f_i)|^2 \} E \{ |g_l(t, f_j)|^2 \}}{|\text{cum} \{ g_k(t, f_i), g_k^*(t, f_i), g_l(t, f_j), g_l^*(t, f_j) \}|}.$$

25 for  $l \leq i, j \leq J$ , and  $i \leq k, l \leq L$ .

where  $g_k(t, f_j)$  denotes the waveform from the  $k^{\text{th}}$  port of the processor in the  $i^{\text{th}}$  band.  $d(i, k; j, l)$  is not a true mathematical metric because it does not satisfy two of the three required metric properties:  $d(i, k; j, l) \neq 0$  and the triangle inequality are not satisfied. Nevertheless, as a pseudo-metric, it does enable port associations to be found.

5 The next step is to associate ports two at a time. This is done with a clustering algorithm borrowed from the field of statistical pattern recognition. An agglomerative hierarchical clustering algorithm is used. Standard algorithms for such clustering are described in textbooks (e.g., Richard O. Duda and Peter E. Hart, *Pattern Classification and Scene Analysis*, John Wiley & Sons, 1973, pp. 228-237). This type  
10 of clustering algorithm searches through the inter-port distances to find the two nearest ports. If the distance is below a threshold, the ports are "merged" or associated and all distances to the two ports that are merged are replaced by distances to the new "merged" signal. This process is repeated until only distances greater than the threshold remain. Constraints are imposed on the clustering algorithm to prevent the  
15 merging of same-band ports because, if the ports are from the same processor, they cannot capture the same signal.

The distances between same-band ports are used to compute the threshold that controls whether ports are sufficiently close to permit them to be merged. The threshold is computed by a statistical  $L$ -estimator operating on the same-  
20 band distances. The distances are sorted into ascending order, and a particular distance is selected based on its rank. This distance is multiplied by a constant to obtain the threshold. Both the rank and the constant depend on  $J$  and  $L$  and are chosen to maintain the probability of false port association,  $P_{\text{fpa}}$ , below some small specified level (e.g., 0.001).

25 After the ports are logically merged or associated into clusters, each cluster will correspond to exactly one wideband signal. The final step is to recover the waveforms of the wideband signals. This is done by adding together the output port signals from all the ports merged or associated to each cluster.

**20.0 Conclusion:**

As described in detail above, the present invention provides a cochannel signal processing and separation that has many facets. Implementation of the basic cumulant recovery (CURE) processing engine may take the form of any of the 5 proposed embodiments, including eCURE (as described in Section 3.0), CiCURE (Section 4.0) or pipeCURE (Section 5.0), and its capabilities may be further extended using  $\alpha$ - $\beta$ CURE or  $\mu$ CURE (Section 6.0), wideband processing (Section 19.0), or direct (non-iterative) computation (Section 7.0).

Applications of a selected form of the CURE processing engine are 10 numerous, and probably not all have been described here. Of prime importance is the application of CURE processing to communication systems (described in Sections 8.0 through 12.0), and in particular the concept of diversity path multiple access (DPMA, described in Section 11.0), which not only permits operation in the presence of multipath propagation, but also takes advantage of multiple coherent signals to provide 15 a diversity gain, and uses a generalized steering vector representative of all the multipath components to generate corresponding transmit weight vectors ensuring that each user receives intended transmissions, even in the presence of multipath effects. Other communication system applications include signal recovery in the presence of strong interfering signals (described in Section 10.0), recovery of multimode signals 20 that have been subject to unwanted mode mixing (Section 13.0), and recovery of signal from a bounded waveguide of any type (Section 14.0). Other applications include radio direction finding (Section 15.0), extending the dynamic range of receiver systems (Section 16.0), high density recording (Section 17.0), and complex phase equalization (Section 18.0).

25 It will be appreciated from the foregoing that the present invention represents a significant advance in all of these diverse fields of application. It will also be understood that, although a number of different embodiments and applications of the invention have been described in detail, various modifications may be made without departing from the spirit and scope of the invention. Accordingly, the invention should 30 not be limited except as by the appended claims.

## CLAIMS

We claim:

- 1            1. A signal processing system for deriving output quantities of interest
- 2    from received cochannel input signals, the system comprising:
  - 3            a signal receiving system (20), including means (120) for generating a
  - 4    set of conditioned receiver signals from cochannel signals of any modulation or type
  - 5    received at a sensor array from multiple sources that can vary in power and location;
  - 6            an estimated generalized steering vector (EGSV) generator (22), for
  - 7    computing for each source an EGSV that results in optimization of a utility function
  - 8    that depends on fourth or higher even-order statistical cumulants derived from the
  - 9    received signals, the EGSV being indicative of a combination of signals received at the
  - 10   sensors from a signal source; and
  - 11            a supplemental computation module (24), for deriving output quantities
  - 12   of interest from the conditioned receiver signals and the EGSV.

- 1            2. A signal processing system as defined in claim 1, wherein:
  - 2            the EGSV generator (22) uses an iterative technique to generate the
  - 3    EGSV and includes means for generating successively more accurate EGSVs based on
  - 4    iterative optimization of the utility function.

- 1            3. A signal processing system as defined in claim 2, wherein the means
- 2    for generating successively more accurate EGSVs includes:
  - 3            a linear combiner (26), for repeatedly computing a single channel
  - 4    combined signal from the conditioned receiver signals and an EGSV;
  - 5            means (30) for supplying an initial EGSV to the linear combiner, to
  - 6    produce the initial output of a single channel combined signal;

7 an EGSV computation module (22), for computing successive values of  
8 the EGSV from successive values of the single channel combined signal received from  
9 the linear combiner and the conditioned receiver signals; and

means (34) for feeding the successive values of the EGSV back to the linear combiner for successive iteration cycles; and

12 means (in 22) for terminating iterative operation upon convergence of  
13 the EGSV to a sufficiently accurate value.

1 4. A signal processing system as defined in claim 2, wherein the means  
2 for generating successively more accurate EGSVs includes:

3 a cross-cumulant matrix computation module (40), for generating a  
 4 matrix of cross-cumulants of all combinations of the conditioned receiver signals;

5 a structured quadratic form computation module (42), for computing  
 6 successive cumulant strength functions derived from successive EGSVs and the cross-  
 7 cumulant matrix;

means (30) for supplying an initial EGSV to the structured quadratic form computation module, to produce the initial output of a cumulant strength function;

10 an ESGV computation module (22), for generating successive EGSVs  
11 from successive cumulant strength functions received from the structured form  
12 computation module; and

13 means (34) for feeding the successive values of the EGSV back to the  
14 structured quadratic form computation module for successive iteration cycles; and

means (in 22) for terminating iterative operation upon convergence of the EGSV to a sufficiently accurate value.

5. A signal processing system as defined in claim 1, wherein the EGSV generator uses a direct computational technique to generate the EGSV, and includes:

3 a cross-cumulant matrix computation module (40), for generating a  
 4 matrix of cross-cumulants of all combinations of the conditioned receiver signals; and

5 an EGSV computation module (22') for computing the EGSV directly  
6 from the cross-cumulant matrix by solving a fourth degree polynomial equation.

1 6. A signal processing system as defined in any of claims 1-5, wherein:  
2 the means for generating the set of conditioned signals includes an  
3 eigendecomposition module (182, 184) for generating an estimate of the number of  
4 signal sources, a transformation matrix (186) for conditioning the receiver signals, and  
5 an eigenstructure (138) derived from the receiver signals; and  
6 the EGSV generator employs signals output by the eigendecomposition  
7 module to compute EGSVs.

1 7. A signal processing system as defined in any of claims 1-5, wherein:  
2 the means for generating the set of conditioned signals includes a  
3 covariance matrix computation module (120') and a matrix decomposition module,  
4 (120') for generating a matrix; and  
5 the system further includes a beamformer (124), for generating a  
6 recovered signal from the receiver signals, the EGSV and the matrix obtained from the  
7 matrix decomposition module.

1 8. A signal processing system as defined in any of claims 1-5, wherein:  
2 the means for generating the set of conditioned signals includes an  
3 eigendecomposition module (182, 184) for generating an estimate of the number of  
4 signal sources, a transformation matrix (186) for conditioning the receiver signals, and  
5 an eigenstructure (138) derived from the receiver signals;  
6 the EGSV generator employs signals output by the eigendecomposition  
7 module to compute EGSVs  
8 the system further comprises a multiple port signal recovery unit (242),  
9 including means (242-3.) for matching current EGSVs with EGSVs from a prior data  
10 block to impose waveform continuity from block to block.

1                   9. A signal processing system as defined in any of claims 2-4, wherein:  
2                   signals are processed in successive blocks of data; and  
3                   the initial of EGSVs for each new processing block are computed by a  
4                   means FIG. 19) for combining a prior block EGSV and a cumulant vector derived from  
5                   the utility function.

1                   10. A signal processing system as defined in claim 9, wherein:  
2                   the means for combining takes the sum of the prior block EGSV  
3                   multiplied by a first factor, and the cumulant vector multiplied by a second factor,  
4                   wherein the first and second factors are selected to provide an initial EGSV that  
5                   anticipates and compensates for movement of a signal source.

1                   11. A signal processing system as defined in claim 3, wherein:  
2                   the system functions to separate a plurality ( $P$ ) of received cochannel  
3                   signals (27);  
4                   there is a plurality ( $P$ ) of EGSV generators including  $P$  EGSV  
5                   computation modules (22. $k$ ) and  $P$  linear combiners (26. $k$ ), for generating an equal  
6                   plurality ( $P$ ) of EGSVs associated with  $P$  signal sources; and  
7                   the supplemental computation module (24A) functions to recover  $P$   
8                   separate received signals from the  $P$  generalized steering vectors and the conditioned  
9                   receiver signals.

1                   12. A signal processing system as defined in claim 11, wherein:  
2                   the supplemental computation module includes a recovery beamformer  
3                   weight vector computation module (44), for generating from all of the EGSVs a  
4                   plurality ( $P$ ) of receive weight vectors, and a plurality ( $P$ ) of recovery beamformers  
5                   (46), each coupled to receive one of the  $P$  receive weight vectors and the conditioned  
6                   receiver signals, for generating a plurality ( $P$ ) of recovered signals.

1                   13. A signal processing system as defined in claim 4, wherein:  
2                   the system functions to separate a plurality ( $P$ ) of received cochannel  
3                   signals;

4                   there is a plurality ( $P$ ) of EGSV generators, including  $P$  EGSV  
5                   computation modules (22.k) and  $P$  structured quadratic form computation modules  
6                   (42.k), for generating an equal plurality ( $P$ ) of EGSVs associated with  $P$  signal  
7                   sources; and

8                   the supplemental computation module (24A) functions to recover  $P$   
9                   separate received signals from the  $P$  generalized steering vectors and the conditioned  
10                  receiver signals.

1                   14. A signal processing system as defined in claim 13, wherein:  
2                   the supplemental computation module (24A) includes a recovery  
3                   beamformer weight vector computation module (44), for generating from all of the  
4                   EGSVs a plurality ( $P$ ) of receive weight vectors, and a plurality ( $P$ ) of recovery  
5                   beamformers (46), each coupled to receive one of the  $P$  receive weight vectors and the  
6                   conditioned receiver signals, for generating a plurality ( $P$ ) of recovered signals.

1                   15. A signal processing system as defined in claim 5, wherein:  
2                   the system functions to separate a two received cochannel signals;  
3                   the ESGV computation module (22') generates two EGSVs from the  
4                   cross-cumulant matrix data; and  
5                   the supplemental computation module (24A) functions to recover two  
6                   separate received signals from the two generalized steering vectors and the conditioned  
7                   receiver signals.

1                   16. A signal processing system as defined in claim 15, wherein:  
2                   the supplemental computation module (24A) includes a recovery  
3                   beamformer weight vector computation module (44), for generating from both of the  
4                   EGSVs two receive weight vectors, and two recovery beamformers (46), each coupled

5 to receive one of the receive weight vectors and the conditioned receiver signals, for  
6 generating two recovered signals.

1 17. A signal processing system as defined in any of claims 1-5, wherein:  
2 the system functions to derive a direction of arrival (DOA) of a received  
3 signal;

4 the supplemental computation module includes a memory (50) for  
5 storing sensor array calibration data, and means (24B) for deriving the DOA of a  
6 received signal from its associated generalized steering vector and the stored sensor  
7 array manifold data.

1 18. A signal processing system as defined in claim 17, wherein:  
2 the sensor array manifold data (50) includes a table associating multiple  
3 DOA values with corresponding steering vectors; and  
4 the means (24B) for deriving the DOA includes means (52) for  
5 performing a reverse table lookup function to obtain an approximated DOA value from  
6 a steering vector supplied by the generalized steering vector generator.

1 19. A signal processing system as defined in claim 18, wherein:  
2 the means (24B) for deriving the DOA further includes means (54) for  
3 interpolating between two DOA values to obtain a more accurate result.

1 20. A signal processing system as defined in any of claims 1-5, wherein  
2 the supplemental computation module (24) includes:  
3 a signal recovery module (24A) for generating received signal  
4 beamformer weights from the conditioned receiver signals and the EGSV; and for  
5 recovering the received signal therefrom; and  
6 a transmitter (56), for generating transmit signal beamformer weights  
7 from the received signal beamformer weights, and for transmitting signals containing  
8 information in a direction determined by the transmit signal beamformer weights.

1                   21. A signal processing system as defined in claims 12 or 14, wherein  
2 the supplemental computation module (24A) further includes:

3                   a transmit weight vector computation module (340), for generating  $P$   
4 transmit beamforming weight vectors from receive weight vectors generated by the  
5 recovery beamformer weight vector computation module; and

6                    $P$  linear combiners (328), for combining each of the  $P$  information  
7 signals to be transmitted with its associated transmit weight vector, to obtain a  
8 weighted transmit beam for each of the information signals to be transmitted, and then  
9 combining corresponding components of the weighted transmit beams, for coupling to  
10 a transmit array (110).

1                   22. A signal processing system as defined in any of claims 11-16,  
2 wherein:

3                   the signal receiving system includes a plurality of waveguide sensors  
4 (64) for receiving signals transmitted onto a waveguide (62) in different modes,  
5 wherein the modes are subject to scrambling in the waveguide; and

6                   the supplemental computation module (24) separates and recovers the  
7 signals and mitigates the effect of mode mixing in the waveguide.

1                   23. A signal processing system as defined in claim 22, wherein the  
2 waveguide is a microwave waveguide.

1                   24. A signal processing system as defined in claim 22, wherein the  
2 waveguide is an optical fiber.

1                   25. A signal processing system as defined in claim 22, wherein the  
2 waveguide is a coaxial cable.

1                   26. A signal processing system as defined in claim 22, wherein the  
2 waveguide includes at least one twisted pair of conductors.

1                   27. A signal processing system as defined in any of claims 11-16,  
2 wherein:

3                   the signals received by the signal receiving system are in-phase and  
4 quadrature components of a two-dimensional communication signal (418), which has  
5 been subject to phase rotation during propagation; and

6                   the recovered signals generated automatically from the supplemental  
7 computation module are in-phase and quadrature components of a two-dimensional  
8 communication signal (424) that has been corrected for phase rotation, wherein the  
9 system functions as a complex phase equalizer.

1                   28. A signal processing system as defined in any of claims 1-5, wherein:  
2                   the signals received by the signal receiving system have been subject to  
3 distortion by analog processing and analog-to-digital conversion in a radio receiving  
4 system (390); and

5                   the output quantities (from 394) include a recovered signal having  
6 significantly less distortion than the received signals, whereby the receiving system has  
7 improved dynamic range as a result of the use of the signal processing system.

1                   29. A signal processing system as defined in any of claims 11-16,  
2 wherein:

3                   the signals received by the signal receiving system (280) include signals  
4 from a relatively weak desired source (286) and much stronger signals from at least  
5 one interfering source (284);

6                   wherein the recovered and separated signals include those from the  
7 relatively weak desired source (286), free of interference, and those from the stronger  
8 interfering source (284), which can be discarded.

1                   30. A method for processing cochannel signals received at a sensor  
2 array, the method comprising the steps of:

3                   conditioning a set of signals received at a sensor array from multiple  
4 sources that can vary in power and location;

5                   generating for each source an estimated generalized steering vector  
6 (EGSV) that results in optimization of a utility function that depends on fourth or  
7 higher even-order statistical cumulants derived from the received signals, the EGSV  
8 being indicative of a combination of signals received at the sensors from a signal  
9 source; and

10                  performing supplemental computation to derive output quantities of  
11 interest from the conditioned receiver signals and the EGSVs.

1                   31. A method as defined in claim 30, wherein:

2                   the step of generating an EGSV includes providing an initial EGSV and  
3 then iteratively generating successive EGSVs until an acceptable convergence is  
4 attained.

1                   32. A method as defined in claim 31, wherein generating an EGSV  
2 includes:

3                   computing in a linear combiner successive values of a single channel  
4 combined signal derived from an input EGSV and the received signals;

5                   supplying an initial EGSV to the linear combiner;

6                   computing successive EGSVs from the received signals and the  
7 successive values of the single channel combined signal;

8                   feeding the successive EGSVs back to the linear combiner for further  
9 iteration; and

10                  terminating further iteration when the EGSV has satisfactorily  
11 converged.

1                   33. A method as defined in claim 31, wherein generating an EGSV  
2 includes:  
3                   computing a matrix of cross-cumulants of the received signals;  
4                   computing in a structured quadratic form computation module successive  
5 values of a cumulant strength function derived from an input EGSV and the cross-  
6 cumulants of the received signals;  
7                   supplying an initial EGSV to the structured quadratic form computation  
8 module;  
9                   computing successive EGSVs from the successive values of the cumulant  
10 strength;  
11                   feeding the successive EGSVs back to the structured quadratic form  
12 computation module for further iteration; and  
13                   terminating further iteration when the EGSV has satisfactorily  
14 converged.

1                   34. A method as defined in claim 30, wherein generating an EGSV  
2 includes:  
3                   generating a matrix of cross-cumulants of all combinations of the  
4 received signals; and  
5                   computing the EGSV directly from the cross-cumulants by solving a  
6 fourth degree polynomial equation.

1                   35. A method as defined in any of claims 30-34, wherein:  
2                   conditioning the received signals includes generating by eigendecom-  
3 position an estimate of the number of signal sources, a transformation matrix for  
4 conditioning the receiver signals, and an eigenstructure derived from the receiver  
5 signals; and  
6                   the step of generating EGSVs employs signals generated in the foregoing  
7 step of generating by eigendecomposition.

1                   36. A method as defined in any of claims 30-34, wherein:  
2                   conditioning the received signals includes generating a covariance matrix  
3 and generating therefrom another matrix; and  
4                   the method further comprises beamforming to generate a recovered  
5 signal from the receiver signals, the EGSV and the other matrix obtained from the  
6 covariance matrix.

1                   37. A method as defined in any of claims 30-34, wherein:  
2                   conditioning the received signals includes generating by eigendecom-  
3 position an estimate of the number of signal sources, a transformation matrix for  
4 conditioning the receiver signals, and an eigenstructure derived from the receiver  
5 signals;  
6                   the step of generating EGSVs employs signals generated in the foregoing  
7 step of generating by eigendecomposition  
8                   the method further comprises the step of matching current EGSVs with  
9 EGSVs from a prior data block to impose waveform continuity from block to block.

1                   38. A method as defined in any of claims 31-33, wherein:  
2                   signals are processed in successive blocks of data; and  
3                   the method further comprises a step of computing an initial EGSV for  
4 each new processing block by combining a prior block EGSV and a cumulant vector  
5 derived from the utility function.

1                   39. A method as defined in claim 38, wherein:  
2                   the combining step includes taking the sum of the prior block EGSV  
3 multiplied by a first factor, and the cumulant vector multiplied by a second factor,  
4 wherein the first and second factors are selected to provide an initial EGSV that  
5 anticipates and compensates for movement of a signal source.

1                   40. A method as defined in claim 32, wherein:  
2                   the method separates a plurality ( $P$ ) of received cochannel signals;  
3                   the step of generating an EGSV is performed in a plurality ( $P$ ) of EGSV  
4                   generators, including  $P$  EGSV computation modules and  $P$  linear combiners, for  
5                   generating an equal plurality ( $P$ ) of EGSVs associated with  $P$  signal sources; and  
6                   the step of performing supplemental computation includes recovering  $P$   
7                   separate received signals from the  $P$  generalized steering vectors and the conditioned  
8                   receiver signals.

1                   41. A method as defined in claim 40, wherein:  
2                   the step of performing supplemental computation further includes  
3                   generating, in a recovery beamformer weight vector computation module, from all of  
4                   the EGSVs a plurality ( $P$ ) of receive weight vectors, and generating a plurality ( $P$ ) of  
5                   recovered signals in a plurality ( $P$ ) of recovery beamformers, each coupled to receive  
6                   one of the  $P$  receive weight vectors and the conditioned receiver signals.

1                   42. A method as defined in claim 33, wherein:  
2                   the system functions to separate a plurality ( $P$ ) of received cochannel  
3                   signals;  
4                   the step of generating EGSVs includes generating a plurality ( $P$ ) of  
5                   EGSVs associated with  $P$  signal sources; and  
6                   the step of performing supplemental computation includes recovering  $P$   
7                   separate received signals from the  $P$  generalized steering vectors and the conditioned  
8                   receiver signals.

1                   43. A method as defined in claim 42, wherein:  
2                   the step of performing supplemental computation further includes  
3                   generating from of the EGSVs, in a recovery beamformer weight vector computation  
4                   module, a plurality ( $P$ ) of receive weight vectors, and generating a plurality ( $P$ ) of

5 recovered signals in a plurality ( $P$ ) of recovery beamformers, each coupled to receive  
6 one of the  $P$  receive weight vectors and the conditioned receiver signals.

1                   44. A method as defined in claim 34, wherein:  
2                   the system functions to separate two received cochannel signals;  
3                   the step of generating EGSVs generates two EGSVs from the cross-  
4                   cumulant matrix data; and  
5                   the step of performing supplemental computation includes recovering  
6                   two separate received signals from the two generalized steering vectors and the  
7                   conditioned receiver signals.

1                   45. A method as defined in claim 44, wherein:  
2                   the step of performing supplemental computation includes generating  
3                   from both of the EGSVs two weight vectors, and generating two recovered signals in  
4                   two recovery beamformers, each coupled to receive one of the weight vectors and the  
5                   conditioned receiver signals.

1                   46. A method as defined in any of claims 30-34, wherein:  
2                   the method functions to derive a direction of arrival (DOA) of a received  
3                   signal;  
4                   the step of performing supplemental computation module storing sensor  
5                   array manifold data in a memory, deriving the DOA of a received signal from its  
6                   associated generalized steering vector and the stored sensor array manifold data.

1                   47. A method as defined in claim 46, wherein:  
2                   the sensor array manifold data includes a table associating multiple DOA  
3                   values with corresponding steering vectors; and  
4                   the step of deriving the DOA includes performing a reverse table lookup  
5                   function to obtain an approximated DOA value from a steering vector supplied by the  
6                   generalized steering vector generator.

1                   48. A method as defined in claim 47, wherein:  
2                   the step of deriving the DOA further includes interpolating between two  
3   DOA values to obtain a more accurate result.

1                   49. A method as defined in any of claims 30-34, wherein the step of  
2   performing supplemental computation includes:  
3                   generating received signal beamformer weights from the conditioned  
4   receiver signals and the EGSV;  
5                   recovering the received signal therefrom;  
6                   generating transmit signal beamformer weights from the received signal  
7   beamformer weights; and  
8                   transmitting signals containing information in a direction determined by  
9   the transmit signal beamformer weights.

1                   50. A method as defined in claim 41 or 43, wherein the step of  
2   performing supplemental computation further includes:  
3                   generating  $P$  transmit beamforming weight vectors from receive weight  
4   vectors generated by the recovery beamformer weight vector computation module; and  
5                    $P$  linear combiners, for combining each of the  $P$  information signals to  
6   be transmitted with its associated transmit weight vector, to obtain a weighted transmit  
7   beam for each of the information signals to be transmitted, and then combining  
8   corresponding components of the weighted transmit beams, for coupling to a transmit  
9   array.

1                   51. A method as defined in any of claims 40-45, wherein:  
2                   the method further comprises receiving signals from a plurality of  
3   waveguide sensors positioned to detect signals transmitted onto a waveguide in  
4   different modes, wherein the modes are subject to scrambling in the waveguide; and

5                   the step of performing supplemental computation includes separating and  
6   recovering the signals, while mitigating the effect of mode mixing in the waveguide.

1                   52. A method as defined in claim 51, wherein the waveguide is a  
2   microwave waveguide.

1                   53. A method as defined in claim 51, wherein the waveguide is an  
2   optical fiber.

1                   54. A method as defined in claim 51, wherein the waveguide is a coaxial  
2   cable.

1                   55. A method as defined in claim 51, wherein the waveguide includes at  
2   least one twisted pair of conductors.

1                   56. A method as defined in any of claims 40-45, wherein:  
2                   the signals received by the signal receiving system are in-phase and  
3   quadrature components of two-dimensional communication signal, which has been  
4   subject to phase rotation during propagation; and

5                   the step of recovering signals automatically generating in-phase and  
6   quadrature components of a two-dimensional communication signal that has been  
7   corrected for phase rotation, wherein the method functions as a complex phase  
8   equalizer.

1                   57. A method as defined in any of claims 30-34, wherein:  
2                   the received signals have been subject to distortion by analog processing  
3   and analog-to-digital conversion in a radio receiving system; and  
4                   the output quantities include a recovered signal having significantly less  
5   distortion than the received signals, whereby the receiving system has improved  
6   dynamic range as a result of the use of the signal processing method.

1                   58. A method as defined in any of claims 40-45, wherein:  
2                   the received signals include signals from a relatively weak desired  
3                   source and much stronger signals from at least one interfering source;  
4                   wherein the step of recovering the signals includes recovering a signal  
5                   from the relatively weak desired source, free of interference, and discarding signals  
6                   from the stronger interfering source.

1                   59. A method for recovery and separation of multiple cochannel signals  
2                   of any modulation or type received at an array of sensors, the method comprising the  
3                   steps of:  
4                   receiving a plurality of cochannel signals from separate signal sources at  
5                   an array of sensors;  
6                   preprocessing the received signals to provide preprocessed signals;  
7                   coupling the preprocessed signals to a plurality of signal extraction  
8                   ports, which may be in an active state or an inactive state;  
9                   in association with each signal extraction port in the active state,  
10                  generating an estimated steering vector and a recovered signal corresponding to one of  
11                  the signal sources, without regard for manifold data of the sensor array;  
12                  orthogonalizing the estimated steering vectors to ensure that each signal  
13                  extraction port generates a recovered signal for a separate signal source; and  
14                  controlling the steps of orthogonalizing and generating recovered signals  
15                  to ensure an orderly association of signal sources with signal extraction ports.

1                   60. A method as defined in claim 59, wherein the step of preprocessing  
2                   includes:  
3                   estimating the number of signal sources of which the signals are being  
4                   received at the sensor array; and  
5                   transforming the received signals, which have a dimensionality based on  
6                   the number sensors, to preprocessed signals, which have a dimensionality based on the  
7                   estimated number of signal sources.

1                   61. A method as defined in claim 60, wherein the step of preprocessing  
2 further includes:

3                   performing an eigendecomposition of the received signals, to produce  
4 signal subspace and noise subspace eigenvalues and eigenvectors, and noise subspace  
5 eigenvalues and eigenvectors; and

6                   computing a transformation matrix from eigenvalues and eigenvectors,  
7 for use in the transforming step.

1                   62. A method as defined in claim 60, wherein the step of generating an  
2 estimated recovered signal in each active signal recovery port includes:

3                   computing an even-order cumulant vector of fourth or higher order from  
4 the preprocessed signals and auxiliary signals related to the estimated recovered  
5 signals; and

6                   using the even-order cumulant vector to compute an estimated recovered  
7 signal, in an iterative process that rapidly converges on a solution for the recovered  
8 signal.

1                   63. A method as defined in claim 61, wherein the step of generating an  
2 estimated recovered signal includes:

3                   initially selecting a random vector to serve as an initial steering vector  
4  $\mathbf{a}_k$ ;

5                   computing a weight value  $\mathbf{v}_k$  from the steering vector  $\mathbf{a}_k$ , by using the  
6 transformation matrix computed in the preprocessing step, wherein the weight vector  
7 has a dimensionality based on the estimated number of sources  $P_e$  and the weight value  
8 has a dimensionality based on the number sensors in the array;

9                   computing an estimate of the recovered signal  $g_k(t)$  from the value  $\mathbf{v}_k$  and  
10 the preprocessed signal  $\mathbf{y}(t)$ ;

11                   computing an auxiliary signal  $u_k(t)$  from the value  $\mathbf{v}_k$  and the  
12 preprocessed input signal  $\mathbf{y}(t)$ ;

13                   computing a fourth-order cumulant vector  $\mathbf{b}_k$  from the preprocessed  
14 signals  $\mathbf{y}(t)$  and the auxiliary signal  $\mathbf{v}_k$ ;

15 orthogonalizing the cumulant vector  $\mathbf{b}_k$  in the orthogonalizer, to produce  
16 an orthogonalized cumulant vector  $\mathbf{d}_k$ ;

17 deriving an updated steering vector  $\mathbf{a}_k$  from the orthogonalized cumulant  
18 vector  $\mathbf{d}_k$ ; and

19 repeating the steps of computing the value  $v_k$ , computing an estimate of  
 20 the recovered signal, computing an auxiliary signal  $u_i(t)$ , computing a fourth-order  
 21 cumulant, orthogonalizing, and deriving an updated steering vector, until the recovered  
 22 signal converges to an acceptably accurate solution.

1 64. A method as defined in claim 63, wherein the step of generating a  
2 recovered signal further includes:  
3 calculating a capture strength  $c_p$  for the each active port.

1 65. A method as defined in claim 63, and further comprising the step of:  
2 demodulating each of the recovered signals from the signal extraction  
3 ports.

1 66. A method as defined in claim 63, and further comprising the step of:  
2 generating direction finding data, by converting the steering vector from  
3 each active signal extraction port to a corresponding angular position in three-  
4 dimensional space.

1                   67. A method as defined in claim 63, wherein the step of computing a  
2 fourth-order cumulant vector uses as input variables the auxiliary signal  $v_k$ , two  
3 instances of the complex conjugate of the auxiliary signal  $u_k^*(t)$  and the preprocessed  
4 signals  $v(t)$ .

1                   68. A method as defined in claim 64, wherein the controlling step  
2 includes:  
3                   detecting changes in the number of signal sources; and, if the number of  
4 signal sources is changed;

5 identifying which signal extraction port was processing a lost source;  
6 and  
7 identifying which signal extraction port will process a new source.

1 69. A receiver/transmitter system capable of receiving cochannel signals  
2 simultaneously from multiple remote units (310) and transmitting cochannel signals to  
3 the remote units simultaneously, the system comprising:

4 a signal receiving system (20), including means (120) for generating  
5 from signals received at a receive sensor array (110) a set of conditioned receiver  
6 signals;

7 a plurality of estimated generalized steering vector (EGSV) generators  
8 (22), for computing for each transmitting remote unit an EGSV that results in  
9 optimization of a utility function that depends on fourth or higher even-order statistical  
10 cumulants derived from the received signals, each EGSV being indicative of a  
11 combination of signals received at the sensors from the remote unit;

12 a recovery beamformer weight vector computation module (44), for  
13 generating from all of the EGSVs a plurality of receive beamforming weight vectors;

14 a plurality of recovery beamformers (46), each coupled to receive one of  
15 the receive beamforming weight vectors and the conditioned receiver signals, for  
16 generating a plurality of recovered signals;

17 a transmit weight vector computation module (340), for generating  
18 transmit beamforming weight vectors from the receive beamforming weight vectors  
19 generated by the recovery beamformer weight vector computation module; and

20 a plurality of linear combiners (328), for combining each information  
21 signal to be transmitted with an associated transmit weight vector, to obtain a weighted  
22 transmit beam for each of the information signals to be transmitted, and then  
23 combining corresponding components of the weighted transmit beams, for coupling to  
24 a transmit array.

1 70. A receiver/transmitter system as defined in claim 69, wherein:

2 signals received from at least one particular remote unit are propagated  
3 over multiple paths to the receive sensor array;

4 the ESGV associated with the signal received over multiple paths is  
5 representative of a composite of all coherent components of the signal arriving over the  
6 multiple paths, wherein multipath components of the same signal are automatically and  
7 dynamically combined but non-coherent cochannel signals are separated; and

8 the transmit weight vector used to transmit signals back to the particular  
9 remote unit results in transmit array directivity pattern that achieves transmission over  
10 generally the same multiple paths traversed by the received signals, using a weighted  
11 combination of the multiple paths;

12 whereby the receiver/transmitter system achieves diversity gain by  
13 virtue of its combination of multipath components.

1 71. A receiver/transmitter system as defined in claim 69, wherein the  
2 transmit weight vector computation module (340) includes:

3 means for selecting from a plurality of fixed pre-formed transmit weight  
4 vectors, based on the receive beamforming weight vectors.

1 72. A receiver/transmitter system as defined in claim 69, wherein the  
2 transmit weight vector computation module (340) includes:

3 means for generating transmit weight vectors adaptively to reflect as  
4 accurately as possible the characteristics of the receive beamforming weight vectors,  
5 whereby signals are transmitted to the respective remote units with minimum  
6 interference because a transmit weight vector associated with a particular remote unit is  
7 selected to be practically orthogonal to all of the estimated generalized steering vectors  
8 associated with transmissions to and from the other remote units.

1 73. A receiver/transmitter system as defined in claim 72, wherein:  
2 the system includes receive and transmit sensor arrays that are identical  
3 in shape but are scaled in dimension in the same ratio as transmit and receive  
4 frequencies, respectively.

1                   74. A method for using a receiver/transmitter system capable of  
2 receiving cochannel signals simultaneously from multiple remote units and transmitting  
3 cochannel signals to the remote units simultaneously, the method comprising the steps  
4 of:

5                   receiving signals from a receive sensor array;

6                   generating from the received signals a set of conditioned receiver  
7 signals;

8                   computing for each transmitting remote unit an estimated generalized  
9 steering vector that results in optimization of a utility function that depends on fourth  
10 or higher even-order statistical cumulants derived from the received signals, the  
11 estimated generalized steering vector being indicative of a combination of signals  
12 received at the sensors from the remote unit;

13                   generating from all of the generalized steering vectors a plurality of  
14 receive beamforming weight vectors;

15                   generating from the receive beamforming weight vectors and the  
16 conditioned receiver signals a plurality of recovered signals corresponding to the  
17 signals received from the respective remote units;

18                   generating transmit beamforming weight vectors from the receive  
19 beamforming weight vectors;

20                   combining each information signal to be transmitted with an associated  
21 transmit weight vector, to obtain a weighted transmit beam for each of the information  
22 signals to be transmitted; and

23                   combining corresponding components of the weighted transmit beams,  
24 for coupling to a transmit array.

1                   75. A method as defined in claim 74, wherein:

2                   signals received from at least one particular remote unit are propagated  
3 over multiple paths to the receive sensor array;

4                   the estimated generalized steering vector associated with the signal  
5 received over multiple paths is representative of a composite of all coherent

6 components of the signal arriving over the multiple paths, wherein multipath  
7 components of the same signal are automatically and dynamically combined but non-  
8 coherent cochannel signals are separated; and

9 the transmit weight vector used to transmit signals back to the particular  
10 remote unit results in transmit array directivity pattern that achieves transmission over  
11 generally the same multiple paths traversed by the received signals, using a weighted  
12 combination of the multiple paths;

13 whereby the receiver/transmitter system achieves diversity gain by  
14 virtue of its combination of multipath components.

1 76. A method defined in claim 74, wherein the step of generating  
2 transmit beamforming weight vectors includes:

3 selecting from a plurality of fixed pre-formed transmit weight vectors,  
4 based on the receive beamforming weight vectors.

1 77. A method as defined in claim 74, wherein the step of generating  
2 transmit beamforming weight vectors includes:

3 generating transmit weight vectors adaptively to reflect as accurately as  
4 possible the characteristics of the receive beamforming weight vectors, whereby signals  
5 are transmitted to the respective remote units with minimum interference because a  
6 transmit weight vector associated with a particular remote unit is selected to be  
7 practically orthogonal to all of the generalized steering vectors associated with  
8 transmissions to and from the other remote units.

1 78. A method as defined in claim 77, and further comprising:  
2 selecting receive and transmit sensor arrays that are identical in shape  
3 but are scaled in dimension in the same ratio as transmit and receive frequencies.

1 79. A two-way communication system using cochannel signals and  
2 diversity path multiple access (DPMA) for transmission in both directions, the system  
3 comprising:

4 at least one receiver/transmitter base station (302) for communicating  
5 with a plurality of mobile devices (310) having omnidirectional antennas for  
6 transmitting uplink signals at an assigned frequency and receiving downlink signals at  
7 another assigned frequency, wherein the receiver/transmitter base station includes

8 a receive antenna array (110),

9 a plurality of estimated generalized steering vector (EGSV)  
10 generators (22), for computing for each mobile device an EGSV that results in  
11 optimization of a utility function that depends on fourth or higher even-order  
12 statistical cumulants derived from the received signals, the EGSV being  
13 indicative of a combination of uplink signals received at the receive antenna  
14 array from the mobile device over possible multiple paths,

15 receiver processing means (24A) for generating from the EGSVs  
16 a recovered signal corresponding to each uplink signal from a mobile device,  
17 and a receive beamforming weight vector corresponding to the uplink signal,

18 a transmitter (56), including means (340) for generating from  
19 each receive beamforming weight vector a corresponding transmit beamforming  
20 weight vector, and a modulator (342) for modulating a downlink transmission  
21 signal with a desired information signal,

22 a transmit antenna array (110) coupled to the transmitter and  
23 having a similar geometrical shape as the receive antenna array, wherein  
24 downlink transmission signals intended for a particular mobile device are  
25 propagated along generally the same multiple paths as the received uplink  
26 signals from the same mobile device;

27 wherein coherent uplink signals received over multiple paths from the  
28 same mobile device are automatically combined, providing a diversity gain effect that  
29 allows weaker transmissions to be detected, and downlink signals transmitted over the  
30 same multiple paths also benefit from the diversity gain effect and provide a stronger  
31 downlink signal to the mobile device.

1                   80. A two-way communication system as defined in claim 79, wherein  
2 the receiver processing means includes:

3                   a recovery beamformer weight vector computation module (44), for  
4 generating from all of the EGSVs the plurality of receive beamforming weight vectors;  
5 and

6                   a plurality of recovery beamformers (46), each coupled to receive one of  
7 the receive beamforming weight vectors and conditioned receiver signals, for  
8 generating the plurality of recovered signals.

1                   81. A two-way communication system as defined in claim 80, wherein  
2 the transmitter includes:

3                   a transmit weight vector computation module (340), for generating  
4 transmit beamforming weight vectors from the receive beamforming weight vectors  
5 generated by the recovery beamformer weight vector computation module; and

6                   a plurality of linear combiners (328), for combining each information  
7 signal to be transmitted with an associated transmit weight vector, to obtain a weighted  
8 transmit beam for each of the information signals to be transmitted, and then  
9 combining corresponding components of the weighted transmit beams, for coupling to  
10 the transmit antenna array.

1                   82. A two-way communication system as defined in claim 79, wherein:  
2                   the uplink and downlink transmission frequencies are offset from each  
3 other to avoid interference between mobile devices; and  
4                   the transmit antenna array has dimensions scaled with respect to those of  
5 the receive antenna array in the inverse ratio of the uplink and downlink transmission  
6 frequencies.

1                   83. A two-way communication system as defined in claim 81, wherein  
2 the transmit weight vector computation module (340) includes:

3                   means for selecting from a plurality of fixed pre-formed transmit weight  
4   vectors, based on the receive beamforming weight vectors.

1                   84. A two-way communication system as defined in claim 81, wherein  
2   the transmit weight vector computation module (340) includes:

3                   means for generating transmit weight vectors adaptively to reflect as  
4   accurately as possible the characteristics of the receive beamforming weight vectors,  
5   whereby downlink signals are transmitted to the respective mobile devices with  
6   minimum interference because a transmit weight vector associated with a particular  
7   mobile device is selected to be practically orthogonal to all of the generalized steering  
8   vectors associated with transmissions to and from the other mobile devices.

1                   85. A method for processing received radio signals that are subject to  
2   unwanted change during propagation, the method comprising the steps of:

3                   transmitting radio signals through the atmosphere;  
4                   subjecting the radio signals to modification as a result of conditions  
5   prevailing during propagation from a transmitter to a receiver array;  
6                   receiving multiple cochannel radio signals at the antenna array; and  
7                   processing the received signals to eliminate the effects of modification of  
8   the signals during propagation, wherein the processing step includes cumulant-based  
9   signal recovery without regard for the geometrical properties of the antenna array.

1                   86. A method as defined in claim 85, wherein:  
2                   the step of transmitting includes transmitting two different information  
3   signals having two different polarization states;  
4                   the step of subjecting the radio signals to modification includes  
5   subjecting at least one of the transmitted signals to a change of its polarization state;  
6                   the step of processing the received signals includes separating and  
7   recovering the two information signals without regard to their polarization states.

1                   87. A method of separating signals transmitted over a waveguide using  
2 different propagation modes in overlapping frequency bands, the method comprising  
3 the steps of:

4                   generating multiple signals in overlapping frequency bands, modulated  
5 by respective information signals using modulation schemes that may be the same for  
6 all of the multiple signals;

7                   transmitting the multiple modulated signals onto an electromagnetic  
8 waveguide, each signal being transmitted in a different propagation mode;

9                   receiving the signals at an array of probes installed in an operative  
10 relationship to the waveguide; and

11                   separating the received signals using a recovery system based on  
12 cumulants of the fourth or higher even order.

1                   88. Communication apparatus for transmitting and receiving signals over  
2 a waveguide using different propagation modes in spectrally-overlapping frequency  
3 bands, the apparatus comprising:

4                   a waveguide (370) serving as a signal transmission medium;

5                   a plurality of signal couplers (374) for injecting modulated signals onto  
6 the waveguide in different electromagnetic propagation modes that are spectrally-  
7 overlapping;

8                   a plurality of signal probes (376) forming a probe array at one or more  
9 places in the waveguide separated from the signal couplers, such that the original  
10 propagation modes are subject to scrambling and distortion as a result of physical  
11 irregularities in the transmission medium; and

12                   a recovery system (378) coupled to the signal probes, to effect recovery  
13 and separation of the signals received at the signal probes, using cumulant  
14 computations based on cumulants of the fourth or higher even order.

1                   89. Communication apparatus as defined in claim 88, wherein:

2 the waveguide (370) is an optical fiber; and  
3 signals are propagated over the waveguide using different frequency  
4 bands of light (wavelength division multiplexing).

allocating up to  $N$  users the same bandwidth sharing parameter, such  
 that the up to  $N$  users share the same frequency band at the same time;  
 receiving signals from up to  $N$  users at an  $M$ -element antenna array; and  
 processing the received signals using a cumulant-based signal recovery  
 system. To separate and recover the signals transmitted by the respective users.

1                   91. A method of separating and recovering communications signals  
2 received in the presence of at least one interfering signal, comprising the steps of:

3 receiving a desired communication signal at an antenna array, from a  
4 communication signal source;

5 simultaneously receiving at the antenna array interfering signals from at  
6 least one interfering signal source at a transmitter, which radiates energy in the same  
7 frequency band as the desired received communication signal;

8 separating and recovering the desired communication signal by using  
9 cumulant-based processing and without knowledge of the geometry of the antenna array  
10 or the nature of the interfering signal; and

11 outputting the desired communication signal and discarding the  
12 recovered interfering signals from the at least one relatively strong transmitter.

- 1                   92. A method of radio direction finding (DF) using a subarray of
- 2   calibrated antennas, the method comprising the steps of:
- 3                   receiving signals from multiple sources, at an antenna array of which
- 4   only a small number of antenna elements are calibrated;

5 separating the signals using a cumulant recovery (CURE) system to  
6 generate the separated signals and estimates of their generalized steering vectors; and  
7 processing the estimated generalized steering vectors and signals from  
8 the calibrated antenna elements, to obtain accurate signal directions for the multiple  
9 sources.

1 93. A method for extending the effective dynamic range of a radio  
2 receiver system, comprising the steps of:

3 receiving a signal of interest through an antenna array;  
4 subjecting the received signal to analog and analog-to-digital processing,  
5 which results in adding products of distortion to the received signal; and  
6 eliminating the principal products of distortion in a cumulant recovery  
7 processing system, and thereby extending the effective dynamic range of the receiver.

1 94. A method for separating data recorded on adjacent, closely spaced  
2 tracks on a recording medium, the method comprising the steps of:

3 sensing information recorded on multiple adjacent tracks on a recording  
4 medium, by means of an array of sensors spanning more than one recording track; and  
5 separating and recovering the information derived from each track,  
6 using a cumulant recovery processing system to process the information sensed by the  
7 array of sensors;

8 whereby information can be recorded at higher densities and still  
9 separated and recovered without improving the accuracy of sensor positioning.

1 95. Apparatus for reading data recorded on adjacent, closely spaced  
2 tracks on a recording medium, the apparatus comprising:

3 an array of sensors (402) spanning more than one recording track on the  
4 recording medium; and  
5 a cumulant recovery processing system (404) for separating and  
6 recovering information derived from each track by the sensors, whereby information

7 can be recorded at high densities and still separated and recovered without the need for  
8 improving sensor positioning accuracy.

1                   96. A method of complex phase equalization for use in a communication  
2 system using two-dimensional signal constellations, the method comprising:

3                   receiving and downconverting a two-dimensional communication signal,  
4 to generate in-phase (I) and quadrature (Q) components that have been phase-rotated by  
5 an unknown amount during propagation from a transmitter;

6                   processing the I and Q signals in a cumulant recovery (CURE)  
7 processing system, to obtain phase correction of the I and Q signals prior to signal  
8 demodulation; and

9                   demodulating the two-dimensional communication signal after the  
10 foregoing processing step, wherein phase correction is effected without regard to  
11 modulation type and independently of the step of demodulating.

1                   97. Complex phase equalizer apparatus for use in a communication  
2 system using two-dimensional signal constellations, the apparatus comprising:

3                   a receiver (416) for receiving a two-dimensional communication signal  
4 (418) and generating in-phase (I) and quadrature (Q) components, wherein the I and Q  
5 components are subject to phase rotation by an unknown angle;

6                   a cumulant recovery (CURE) processing system (420) connected to  
7 receive the I and Q components from the receiver wherein the I and Q signals received  
8 by the CURE processing system are each a linear combination of two independent  
9 source signals, which are the I and Q signals prior to phase rotation, and wherein the  
10 CURE processing system derives the two independent source signals and effectively  
11 compensates for the phase rotation of the I and Q signals; and

12                   a demodulator (422) connected to receive phase-corrected I and Q  
13 signals from the CURE processing system, wherein the CURE processing system  
14 effects phase correction of the communication signals prior to demodulation and  
15 independently of the demodulation type and the demodulation process.

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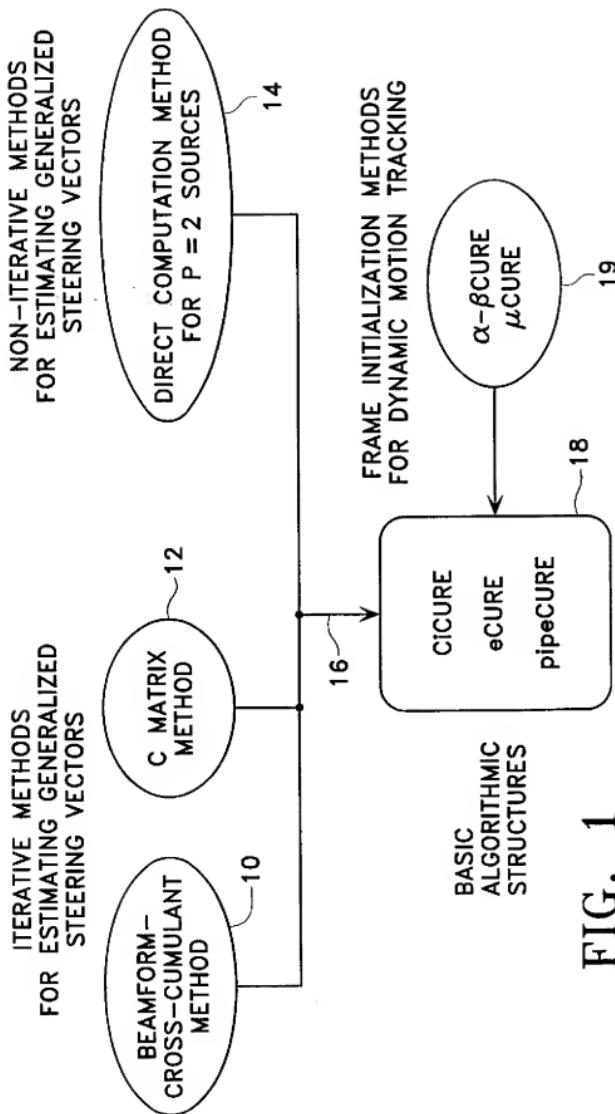


FIG. 1

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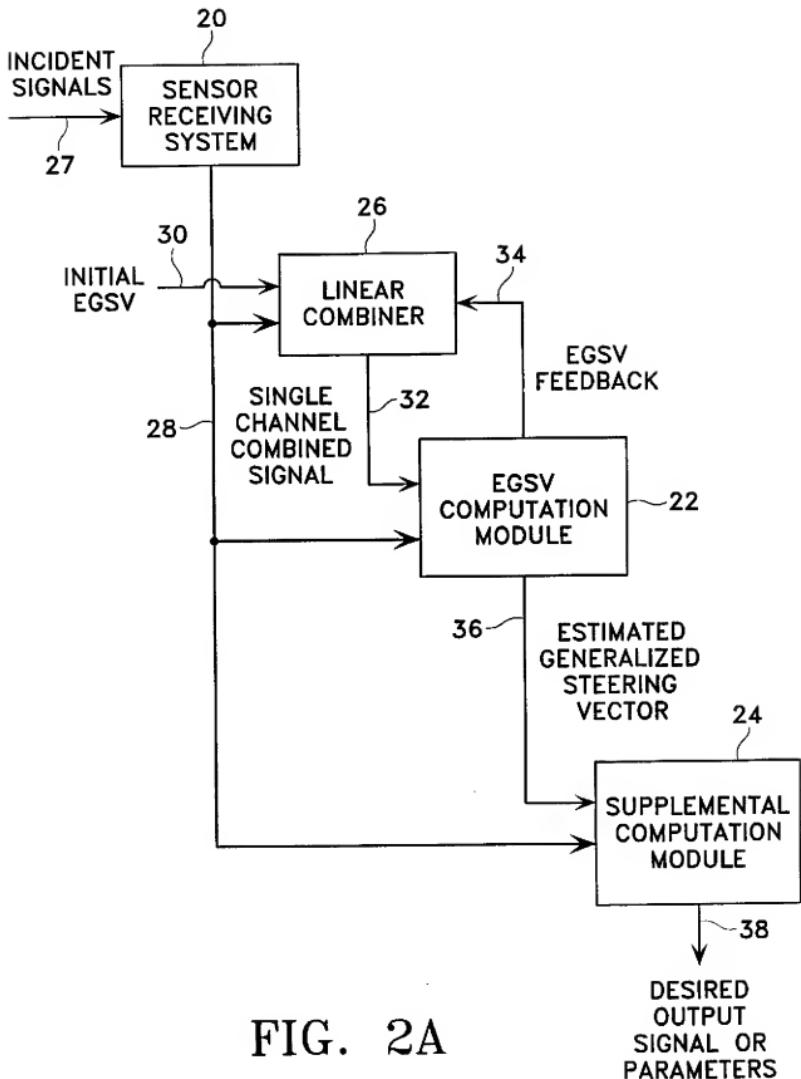


FIG. 2A

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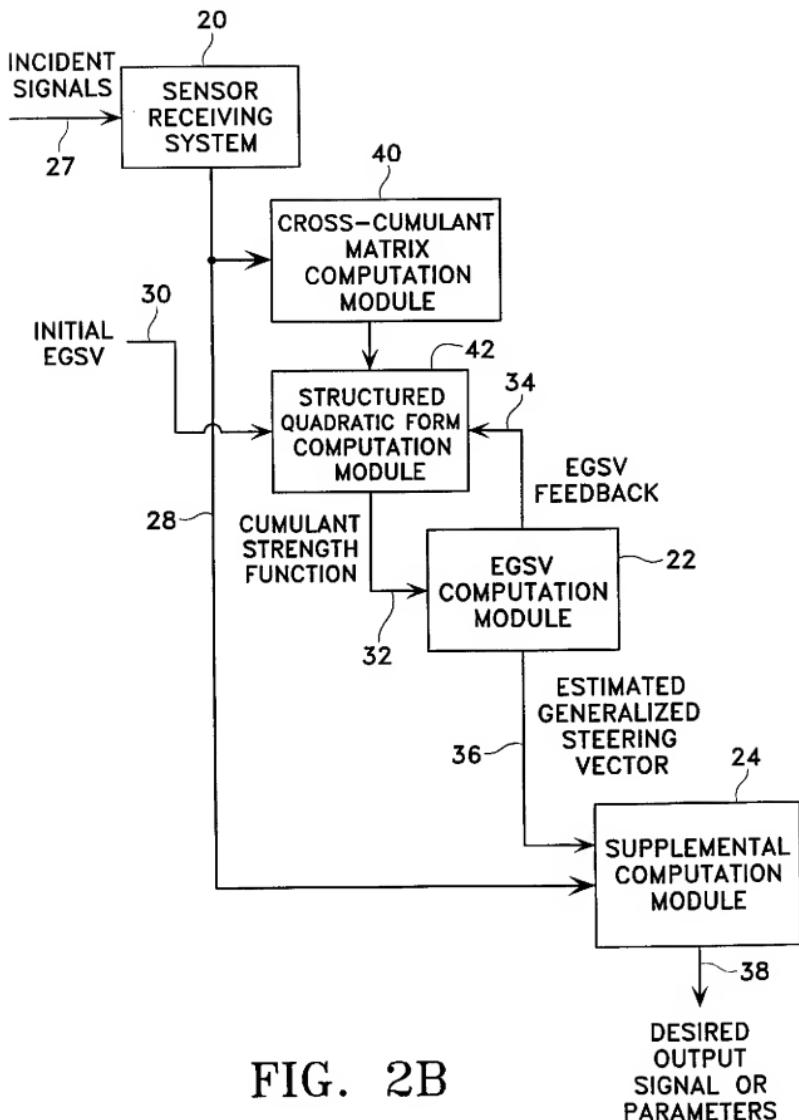


FIG. 2B

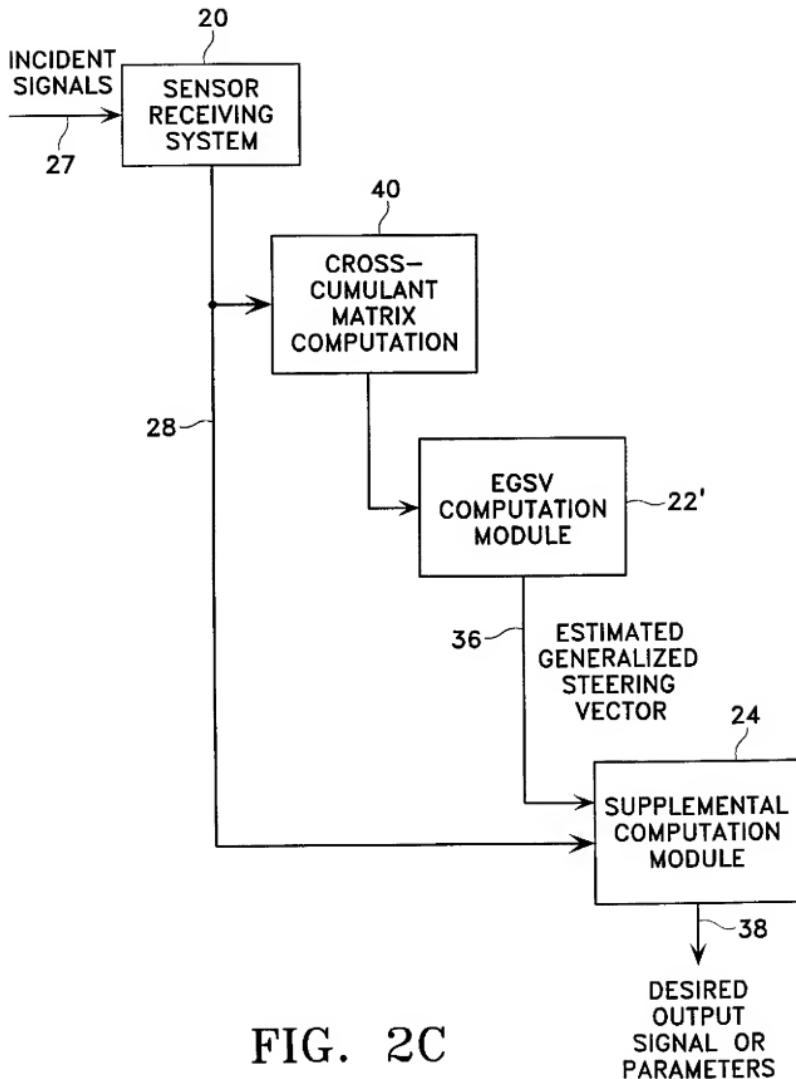


FIG. 2C

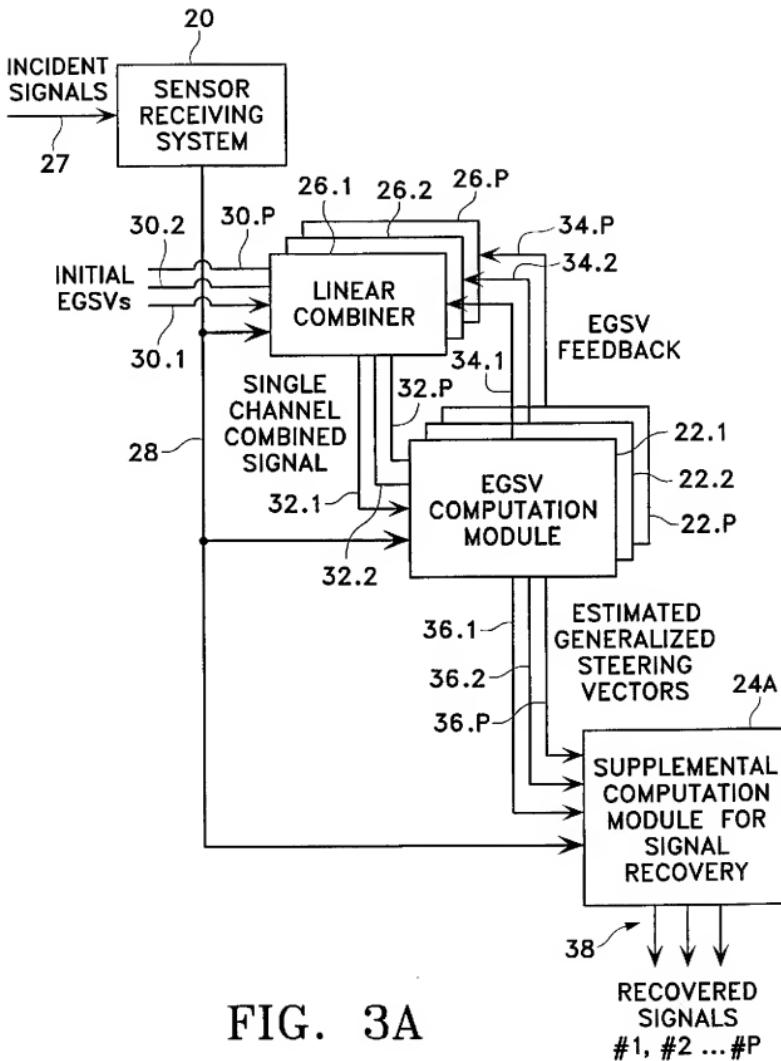


FIG. 3A

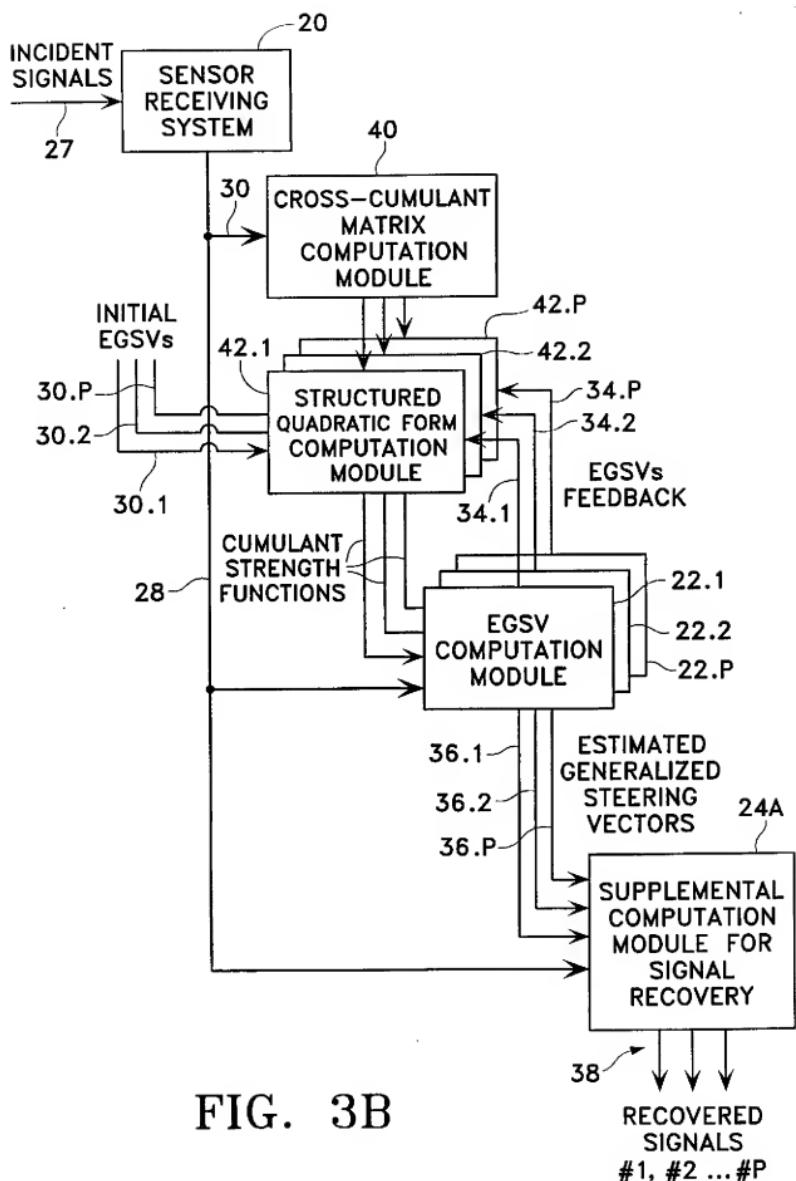


FIG. 3B

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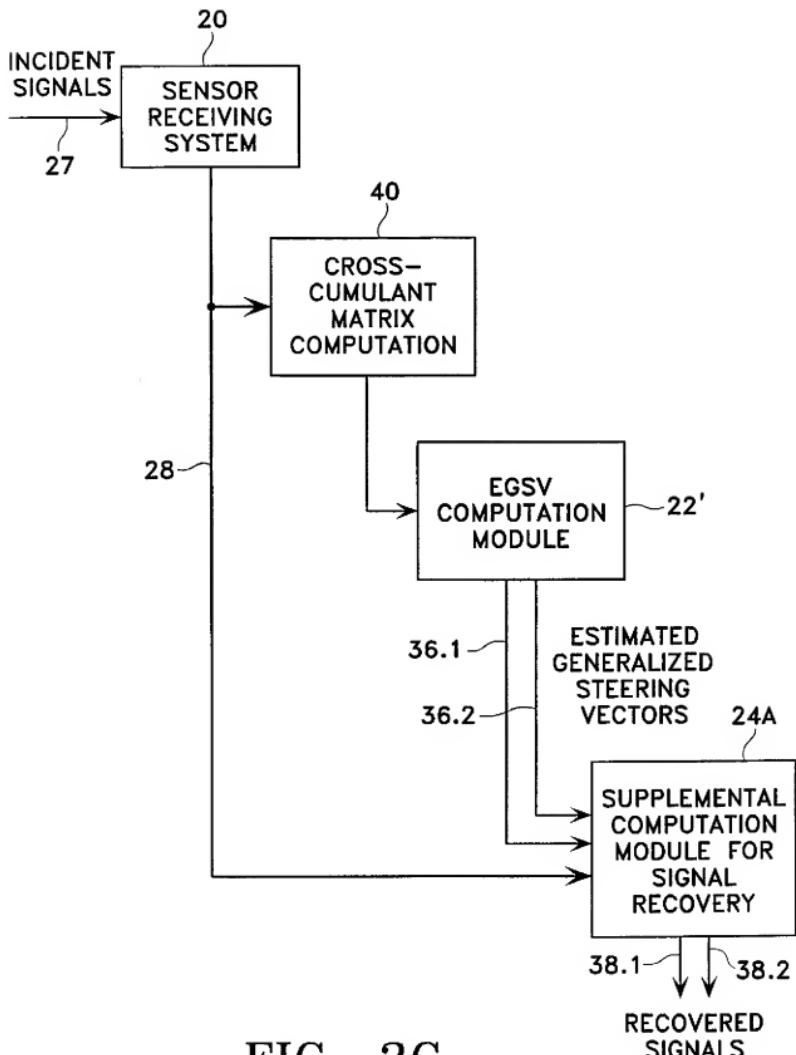


FIG. 3C

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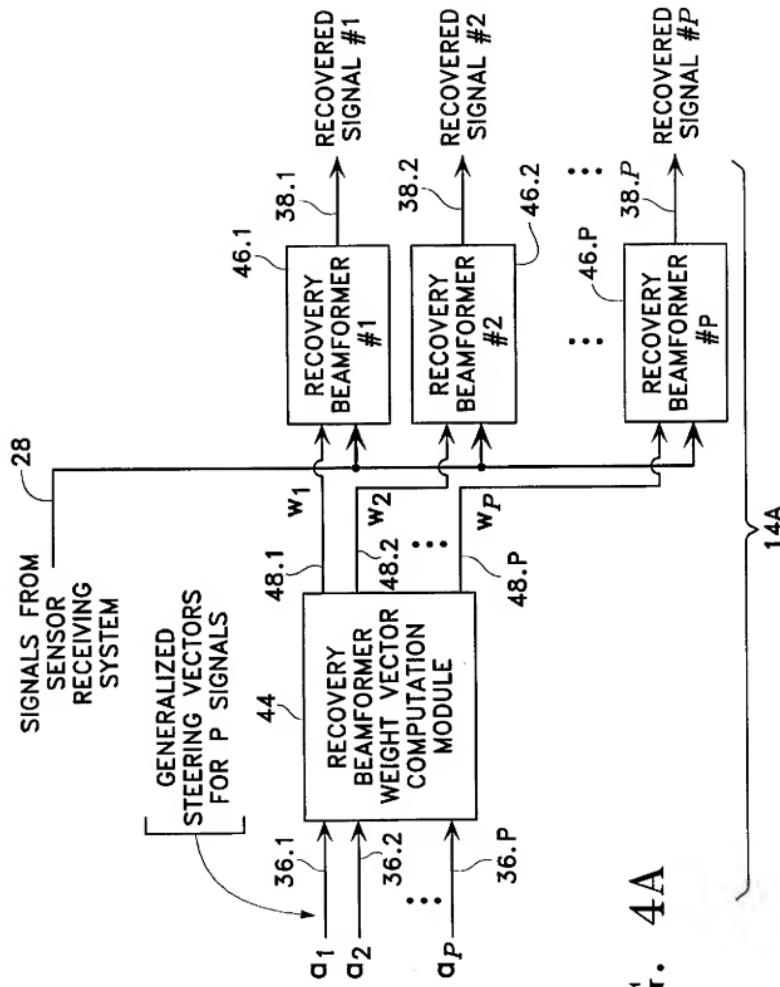


FIG. 4A

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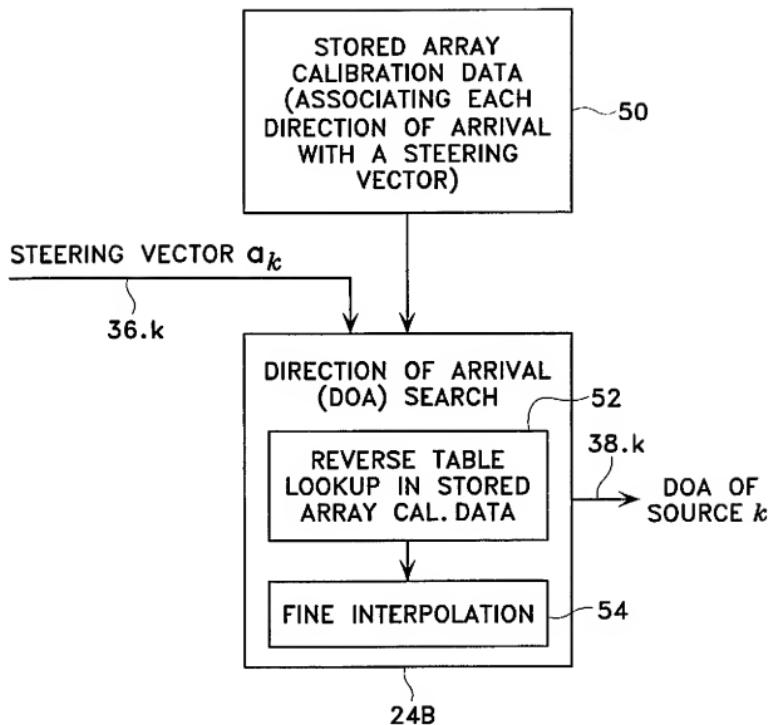


FIG. 4B

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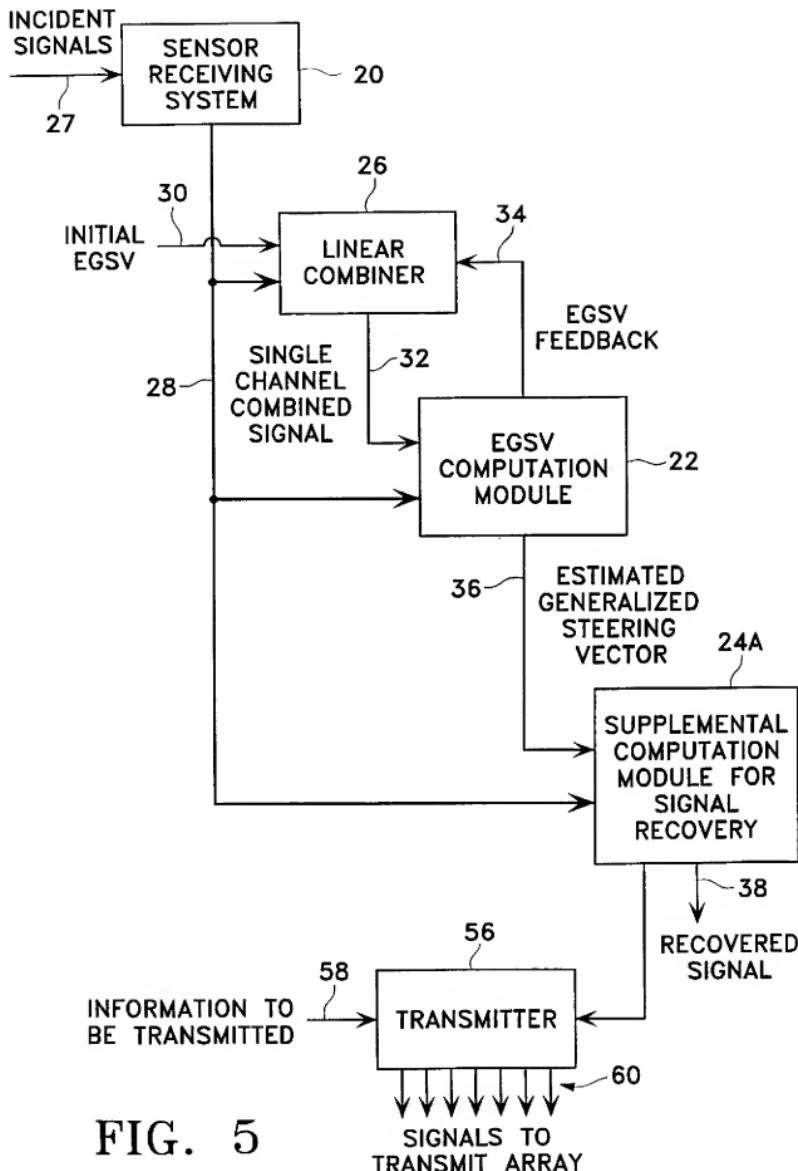


FIG. 5

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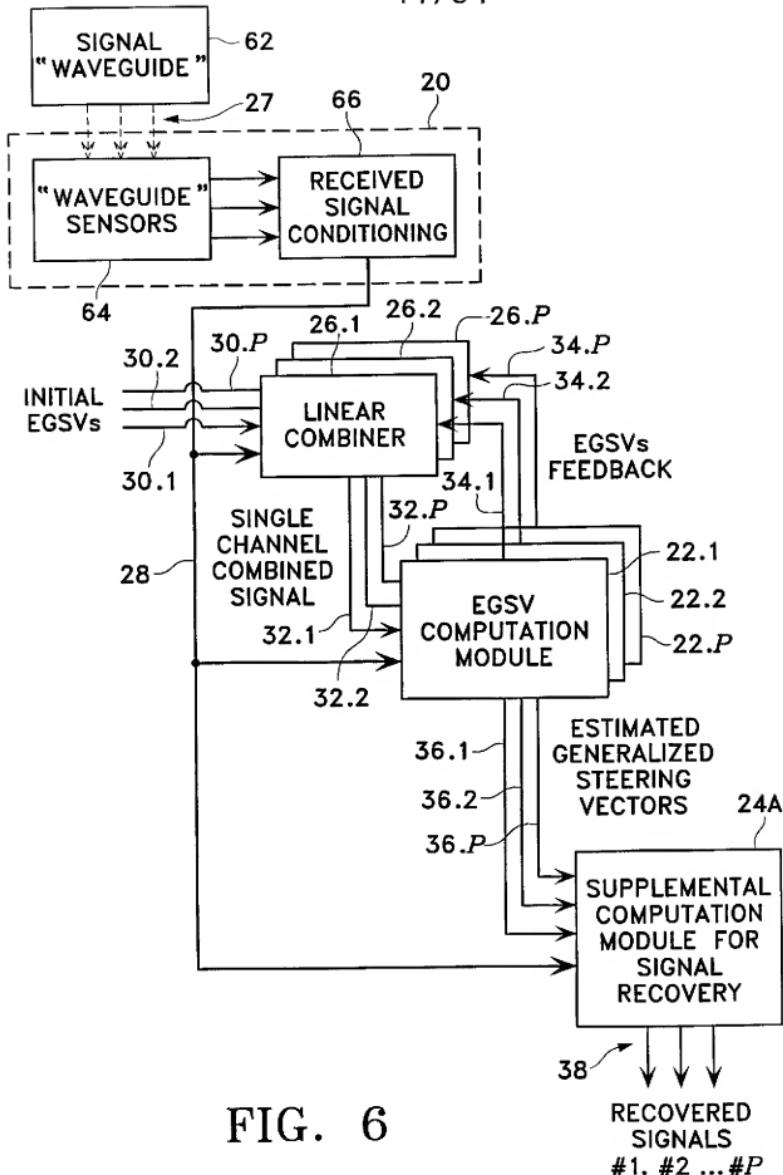


FIG. 6

RECOVERED  
SIGNALS  
#1, #2 ... #P

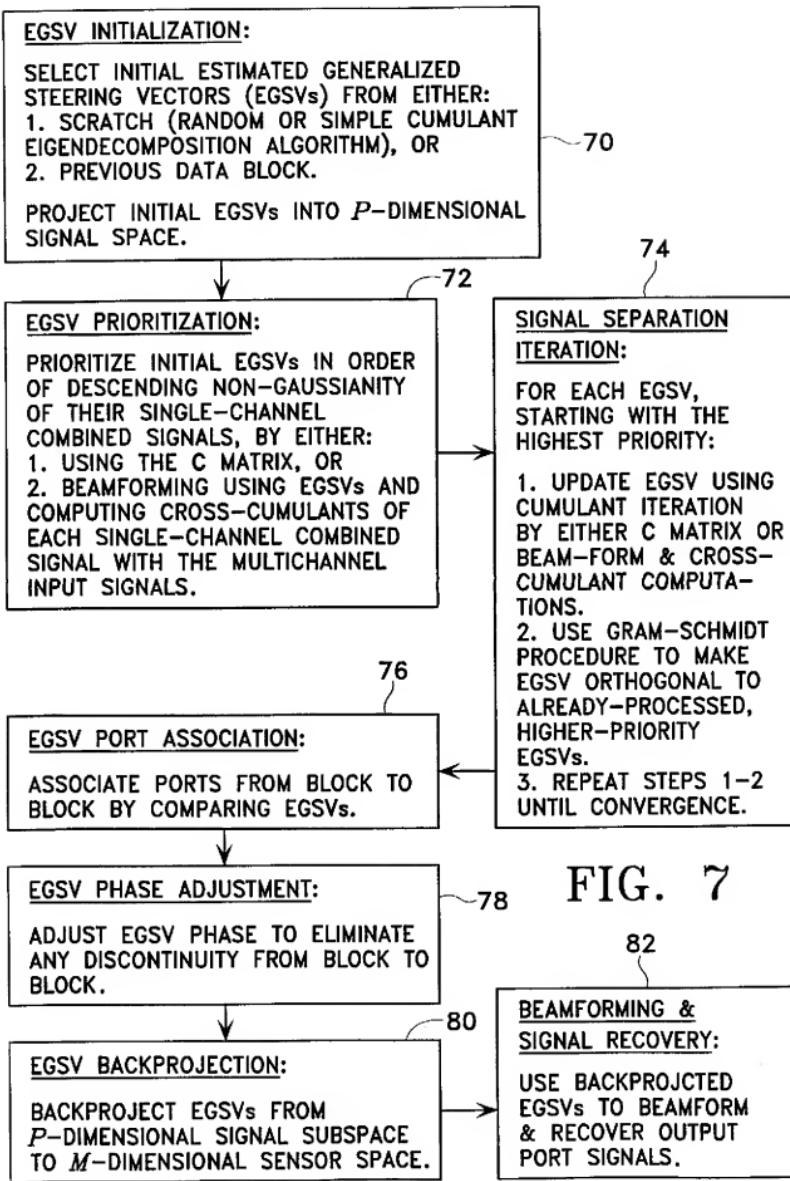


FIG. 7

82

80

78

72

70

74

13 / 51

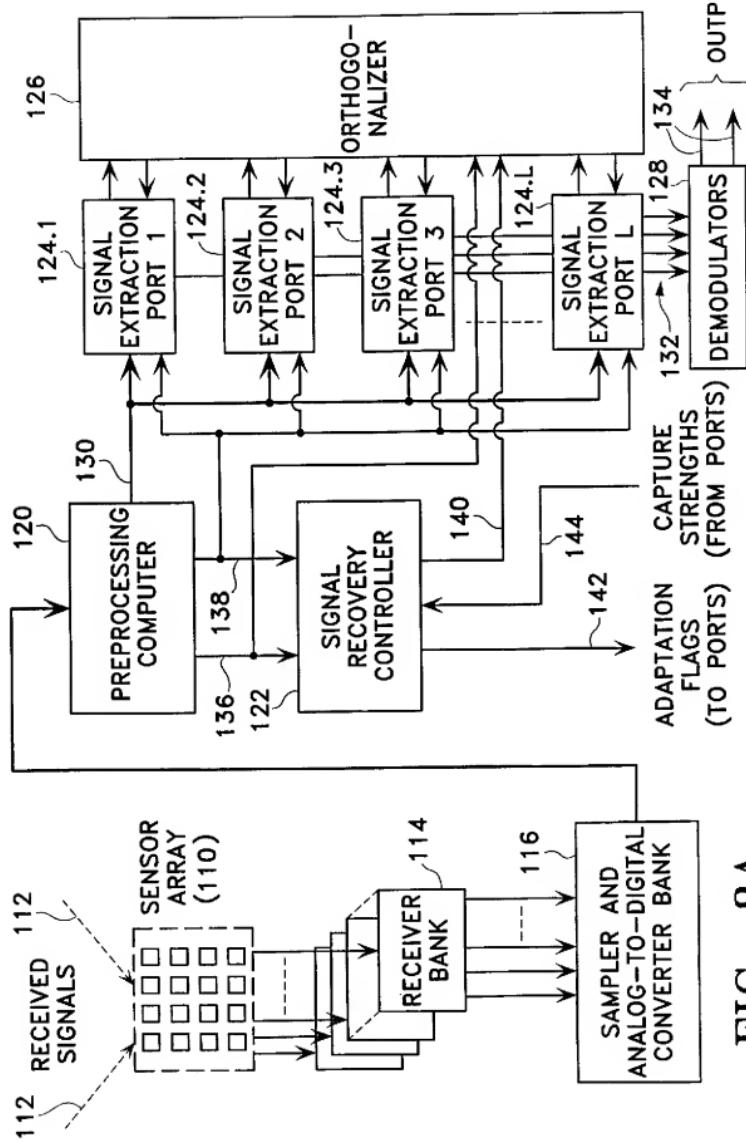
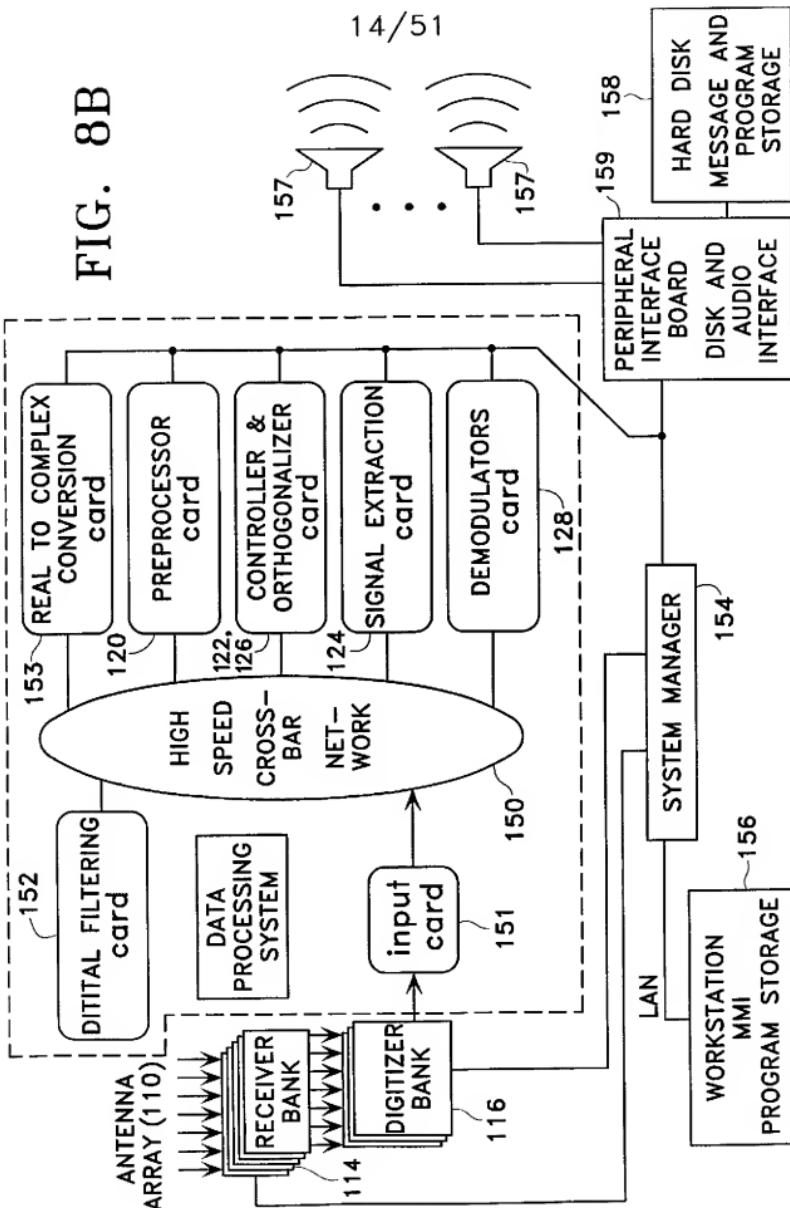


FIG. 8A

FIG. 8B



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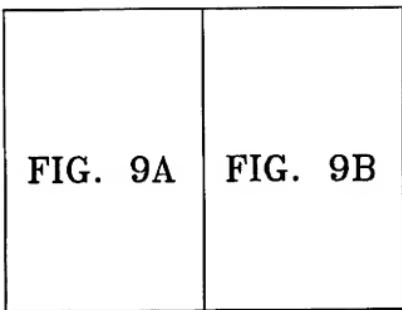


FIG. 9

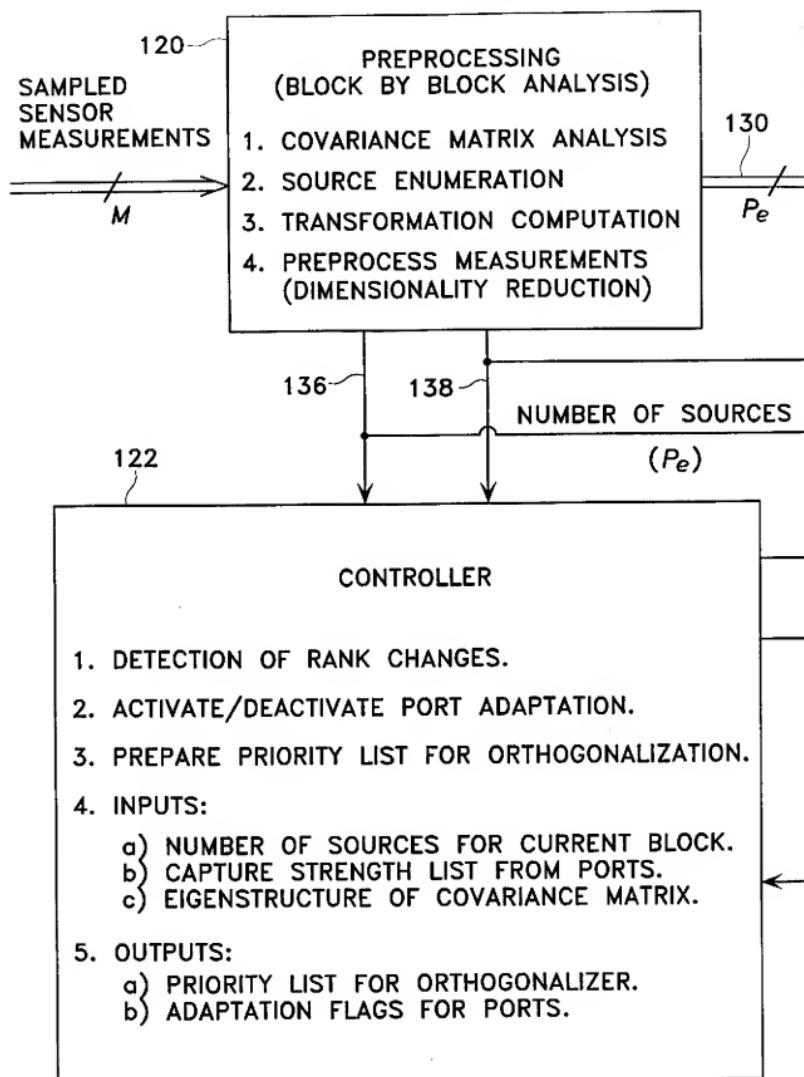


FIG. 9A

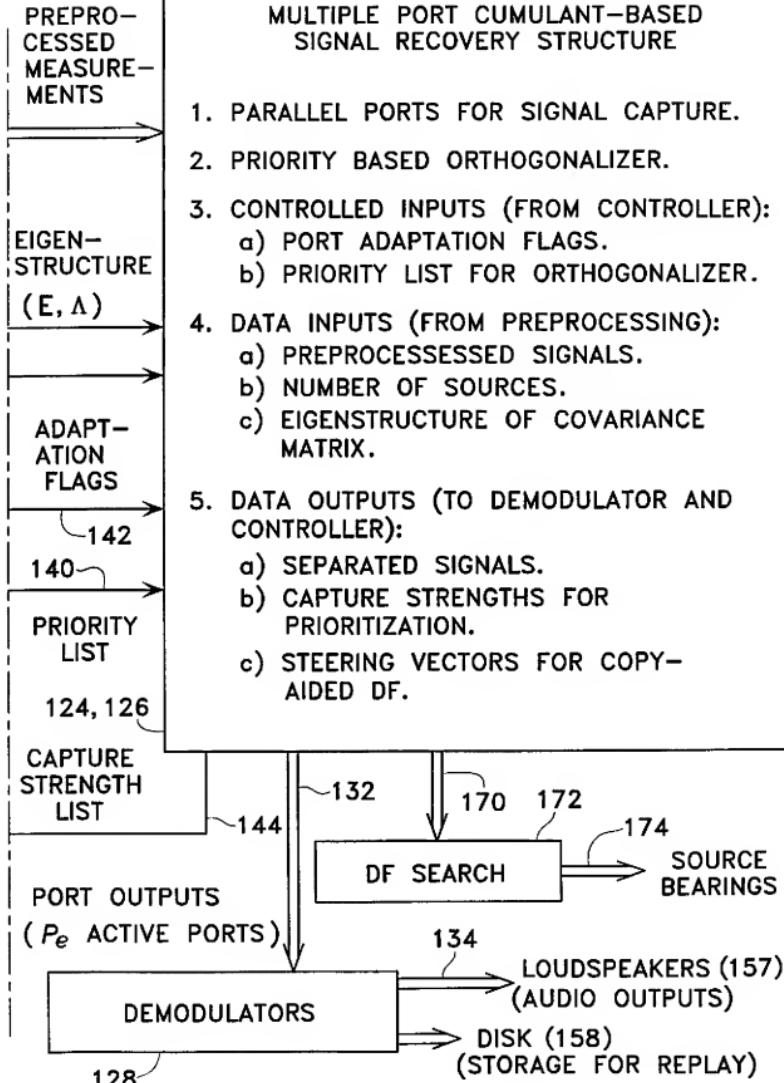


FIG. 9B

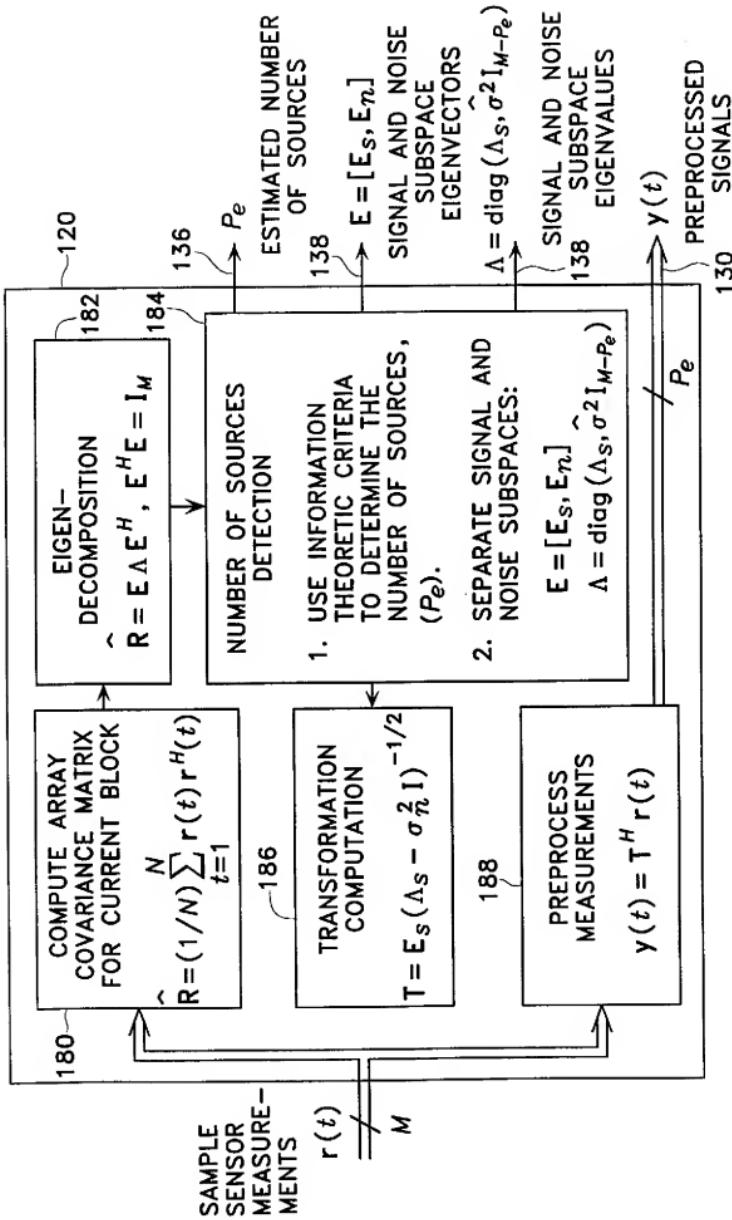


FIG. 10

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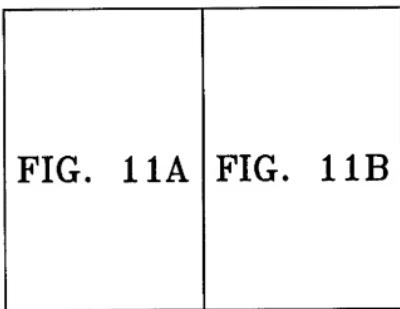


FIG. 11

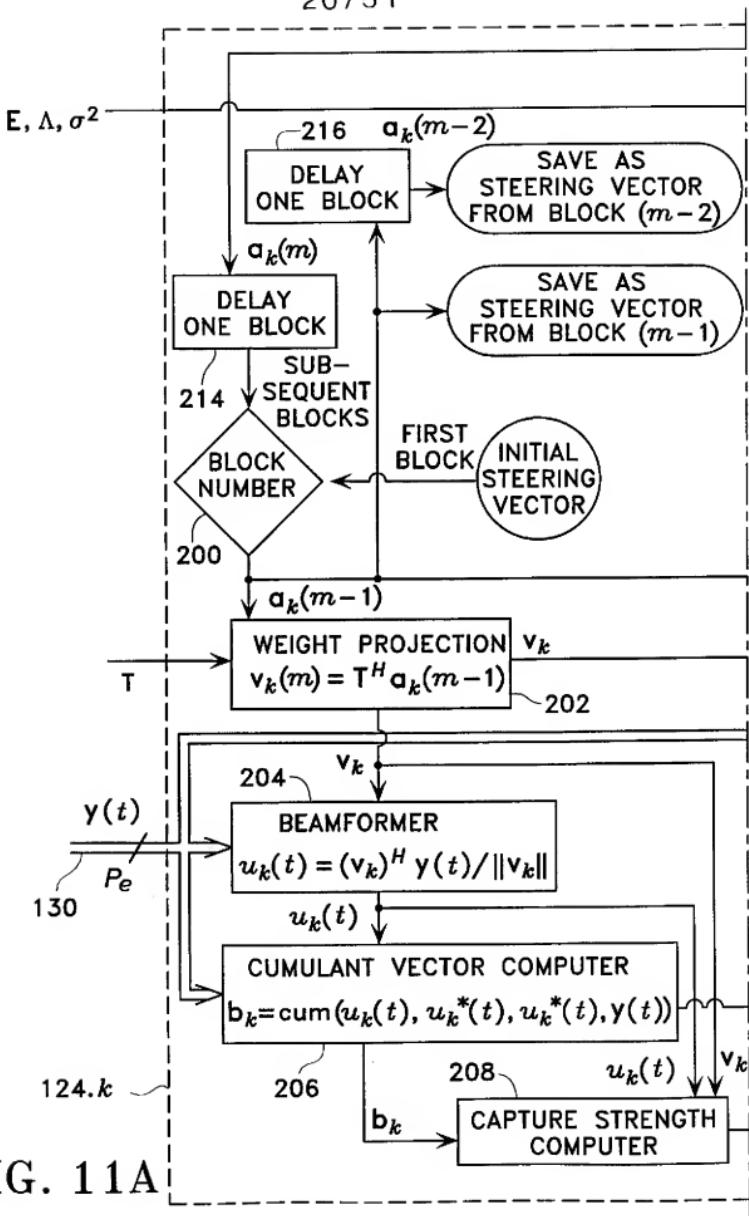


FIG. 11A

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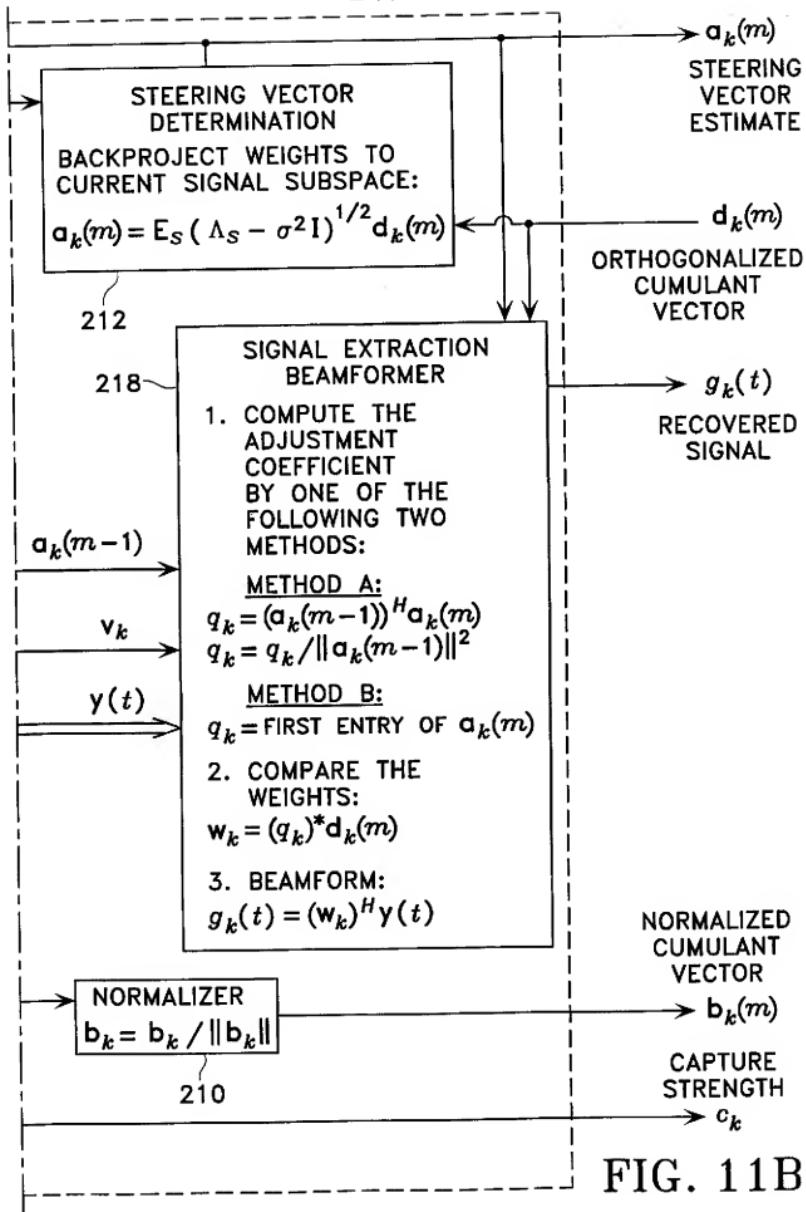
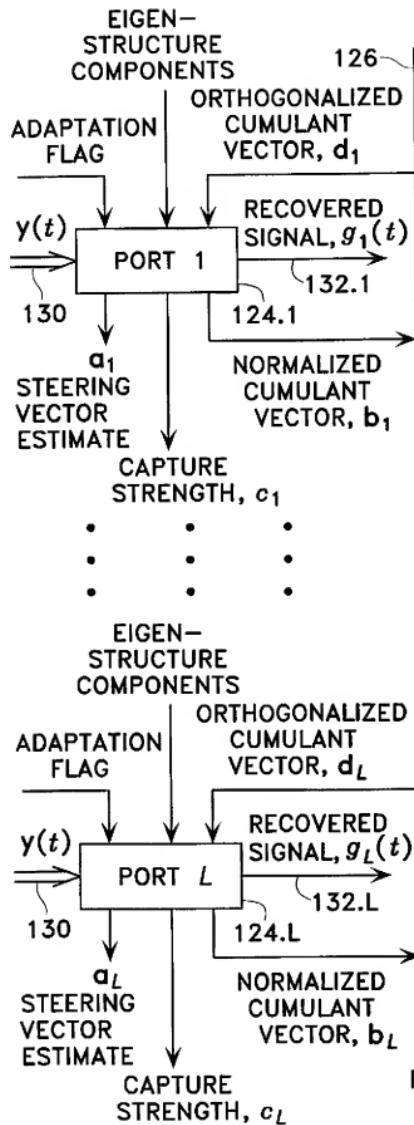


FIG. 11B

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## ORTHOGONALIZER

1. OBTAIN THE CUMULANT VECTORS ( $b_k$ 's) FROM PORTS AND THE PRIORITY LIST (PRIOR) FROM CONTROLLER.
2. FROM THE Z MATRIX FROM THE CUMULANT VECTORS USING THE PRIORITY LIST.
3. APPLY GRAM-SCHMIDT TO Z, TO OTHOGONALIZE THE COLUMNS OF Z.
4. FEEDBACK THE ORTHOGONALIZED CUMULANT VECTORS ( $d_k$ 's) TO PORTS.

PRIORITY  
LIST36  $P_e$ 

FIG. 12

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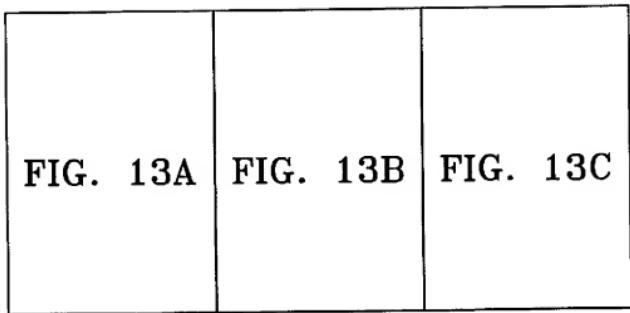
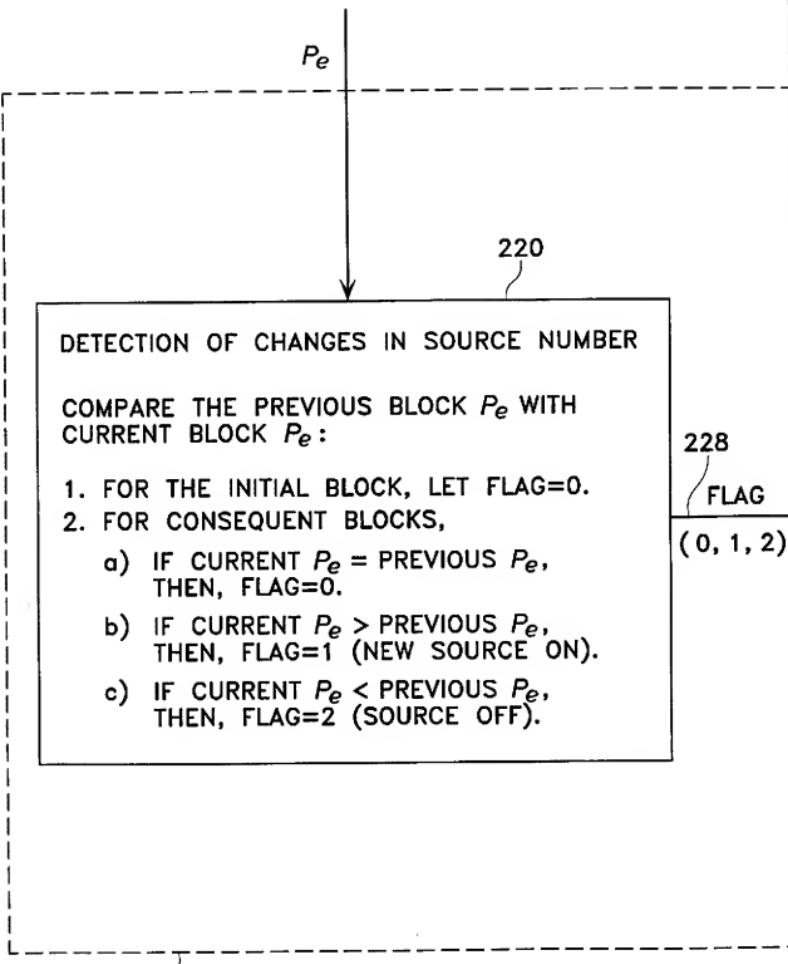


FIG. 13

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22

FIG. 13A

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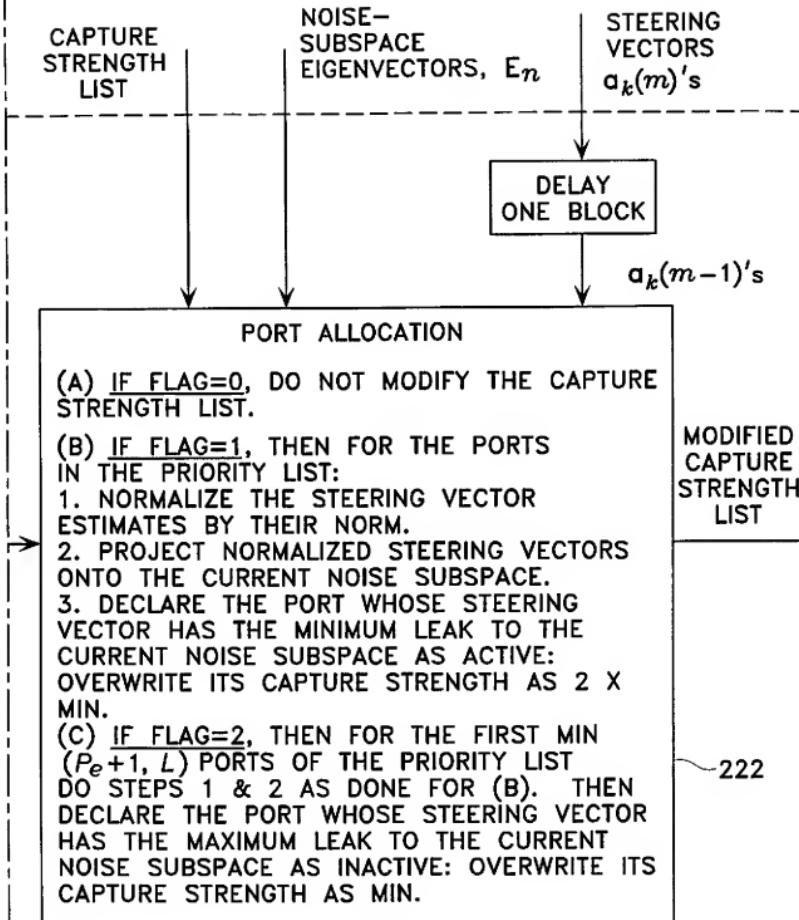


FIG. 13B

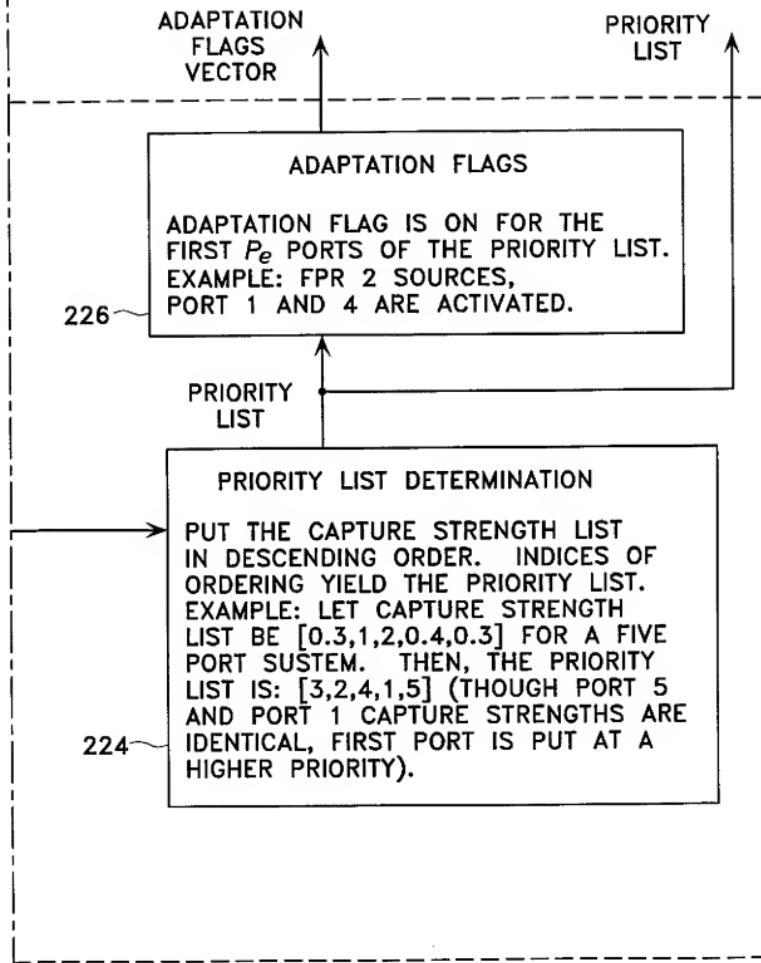


FIG. 13C

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## FLOW OF OPERATIONS WITH PORT ADAPT FLAG = 0

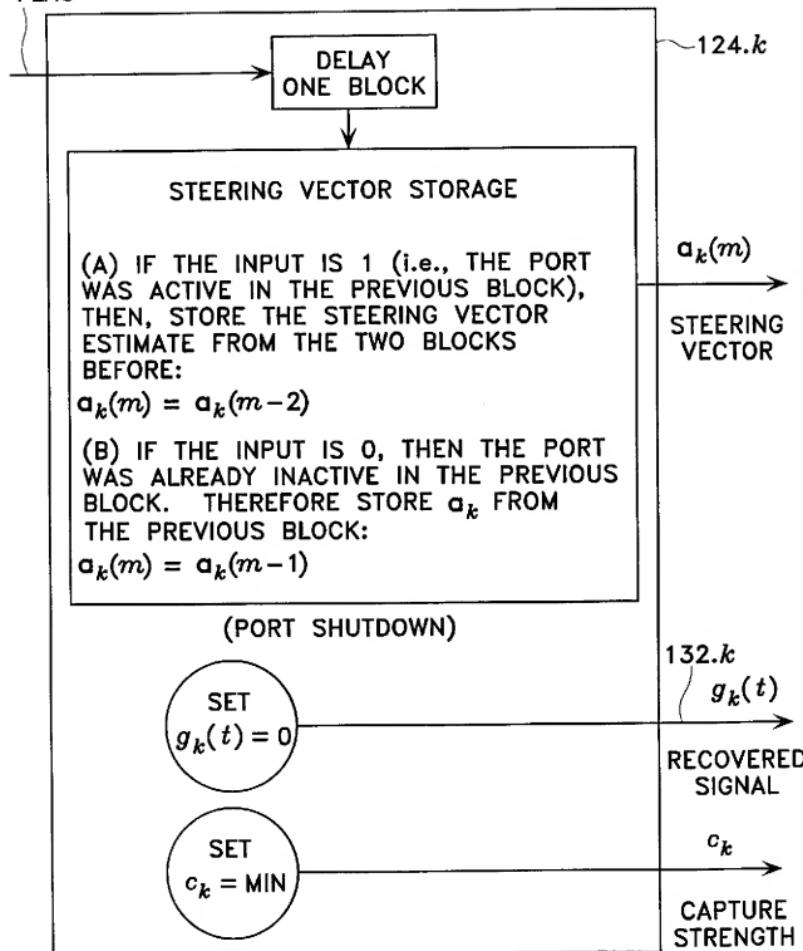
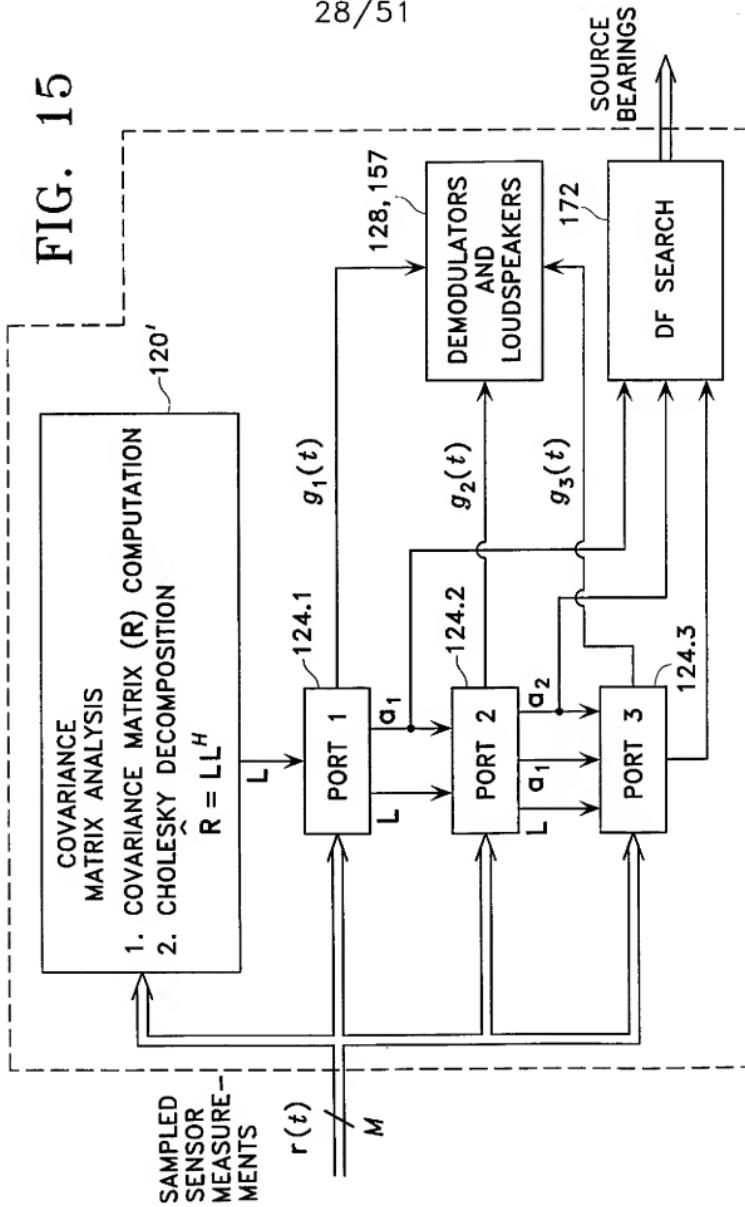
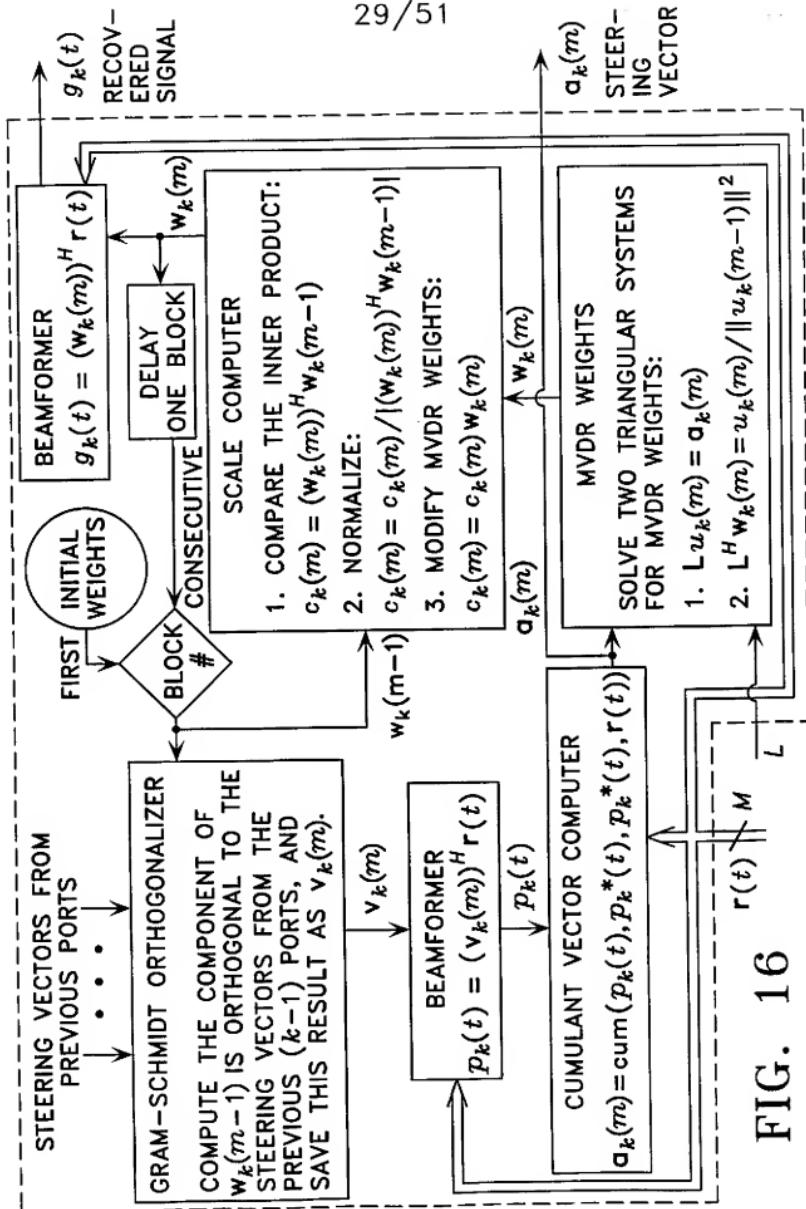
ADAPTATION  
FLAG

FIG. 14

FIG. 15



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120

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SAMPLED  
SENSOR  
MEASUREMENTS $\xrightarrow{M}$ PREPROCESSING  
(BLOCK BY BLOCK ANALYSIS)

1. COVARIANCE MATRIX ANALYSIS
2. SOURCE ENUMERATION
3. TRANSFORMATION COMPUTATION
4. PREPROCESS MEASUREMENTS (DIMENSIONALITY REDUCTION)

PREPROCESSED  
MEASUREMENTS $y(t)$  $P_e$ 

130

138

EIGENSTRUCTURE ( $E, \Lambda$ )NUMBER OF SOURCES ( $P_e$ )

136

FIG. 17A

FIG. 17A

FIG. 17B

FIG. 17

31/51

240

## CUMULANT MATRIX COMPUTER

1. CALCULATES A CUMULANT MATRIX C OF SIZE  $P^2$  BY  $P^2$ , FOR PREPROCESSED MEASUREMENTS.
2. USES ALL OF SYMMETRY PROPERTIES OF CUMULANTS FOR REDUCING COMPUTATIONS.

y(t)

C

242

## MULTIPLE PORT SIGNAL RECOVERY

1. USE PREVIOUS BLOCK STEERING ESTIMATES AND THE CURRENT EIGENSTRUCTURE TO FIND THE EIGENVECTORS AT C BY THE POWER METHOD.
2. USE THE EIGENSTRUCTURE AND ESTIMATED EIGENVECTORS OF C TO ESTIMATE THE CURRENT STEERING VECTORS.
3. MATCH THE CURRENT STEERING VECTORS WITH THE PREVIOUS BLOCK STEERING VECTORS AND IMPOSE WAVEFORM CONTINUITY CONSTRAINTS TO DETERMINE WEIGHT VECTORS FOR CURRENT BLOCK OF DATA.
4. BEAMFORM TO EXTRACT MULTIPLE SOURCE WAVEFORMS.

132

170

STEERING VECTORS

128

172

DF SEARCH

174

SOURCE BEARINGS

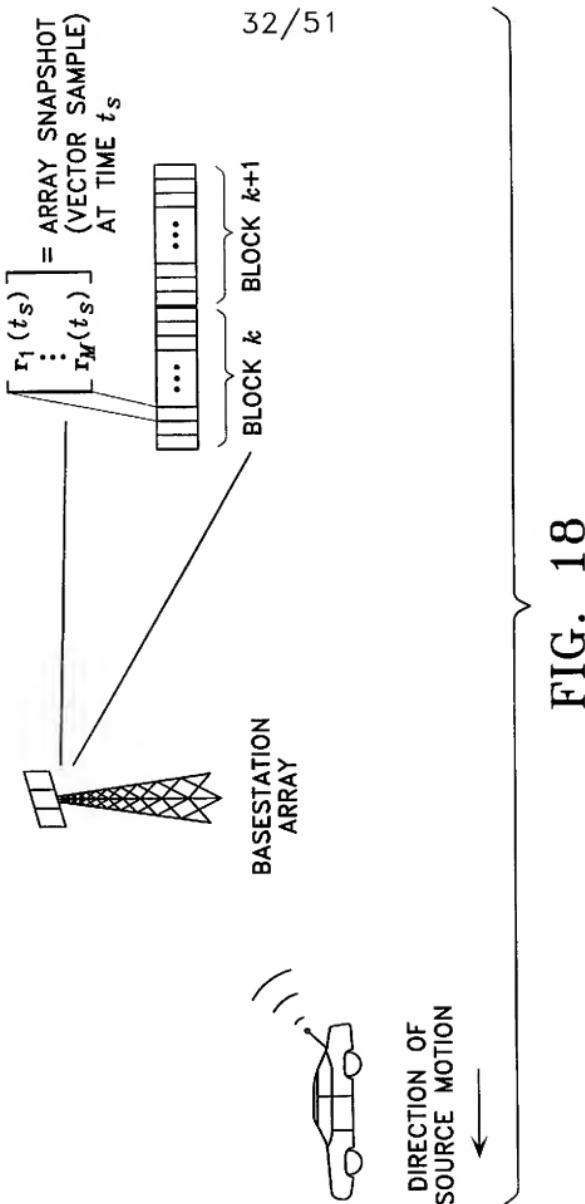
## DEMODULATORS

LOUDSPEAKERS (157)  
(AUDIO OUTPUTS)DISK (158)  
(STORAGE FOR REPLAY)

134

FIG. 17B

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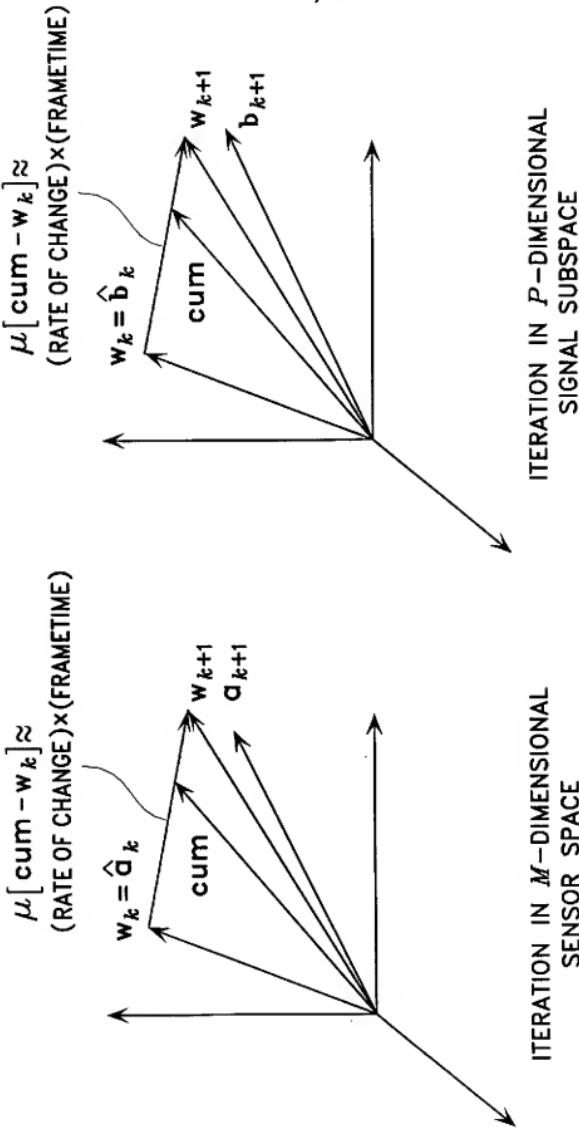
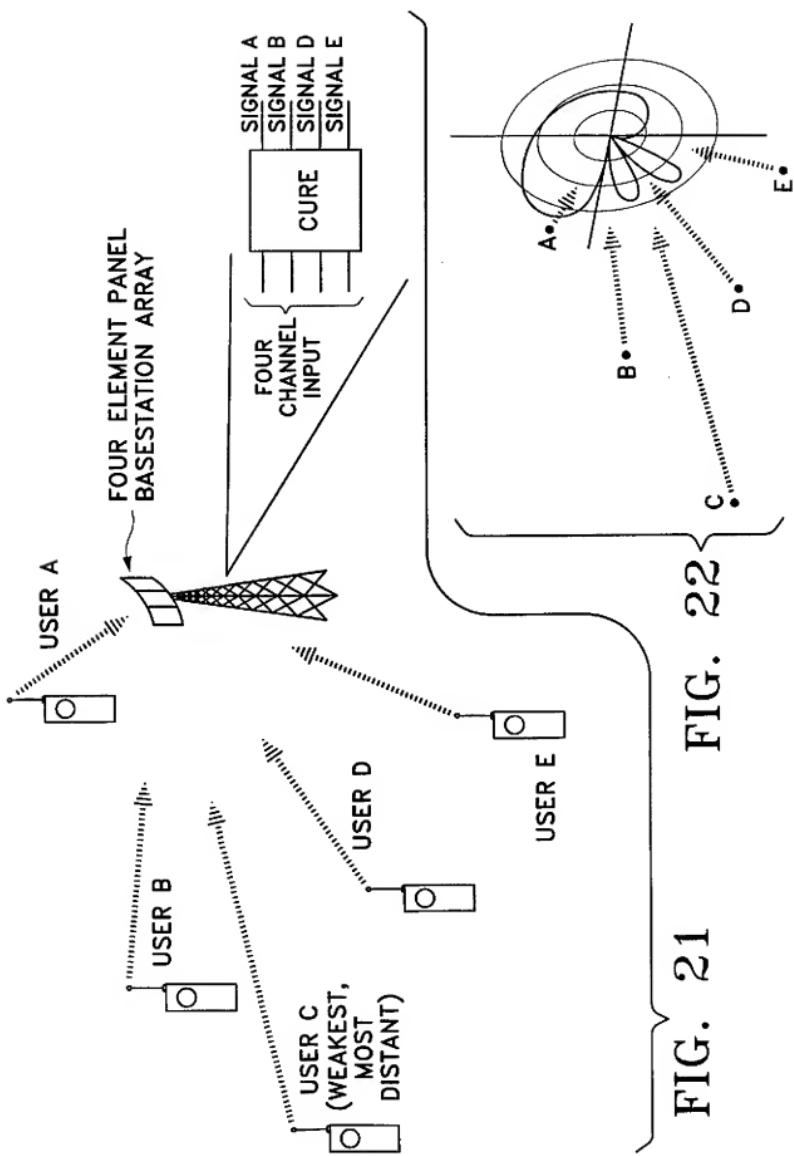


FIG. 19

FIG. 20

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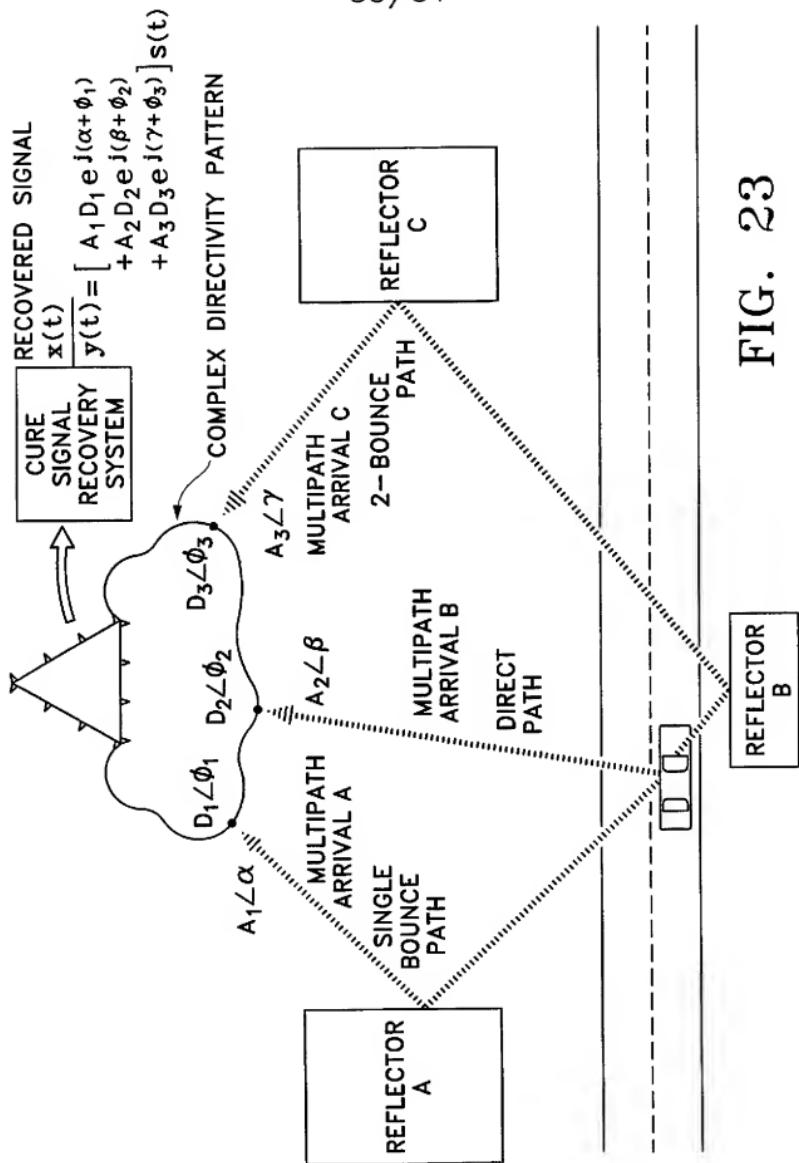


FIG. 23

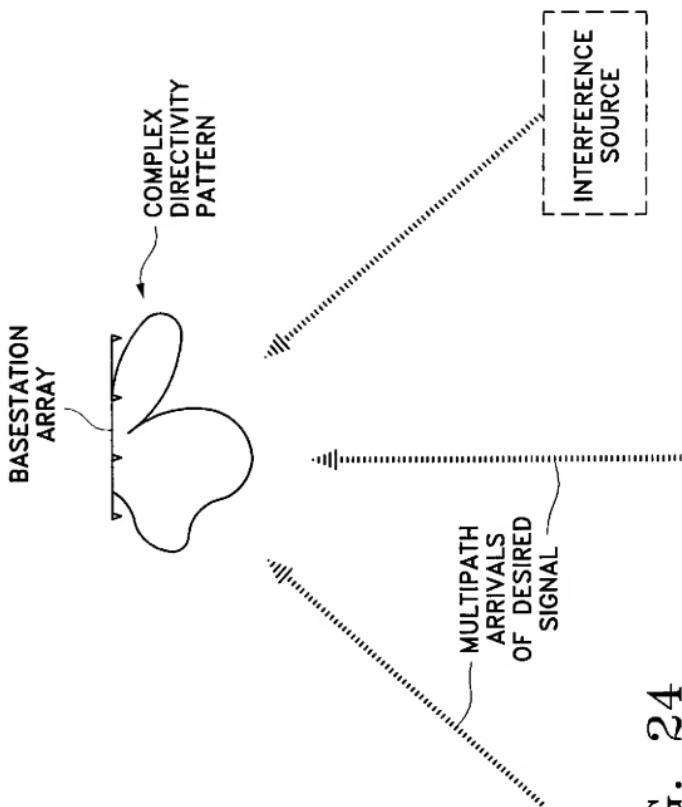


FIG. 24

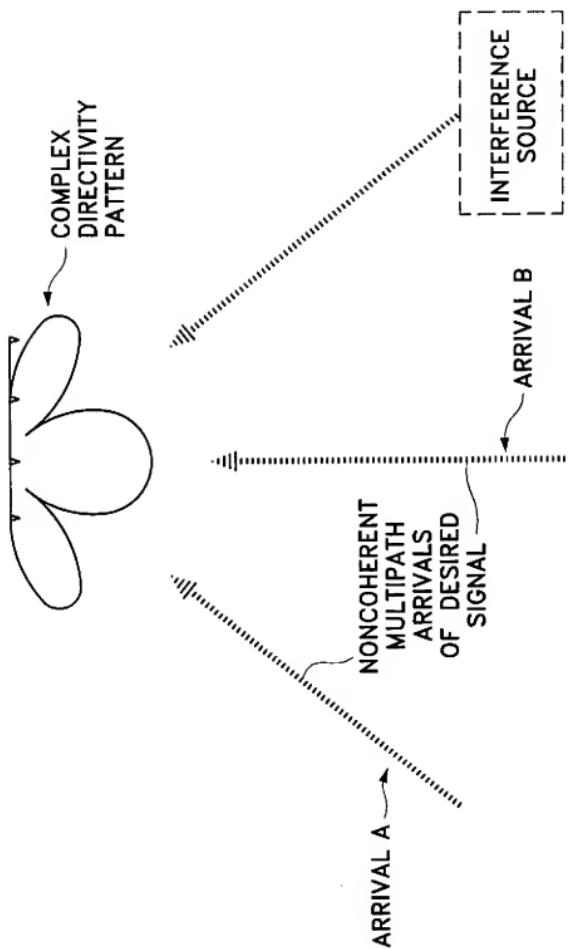


FIG. 25

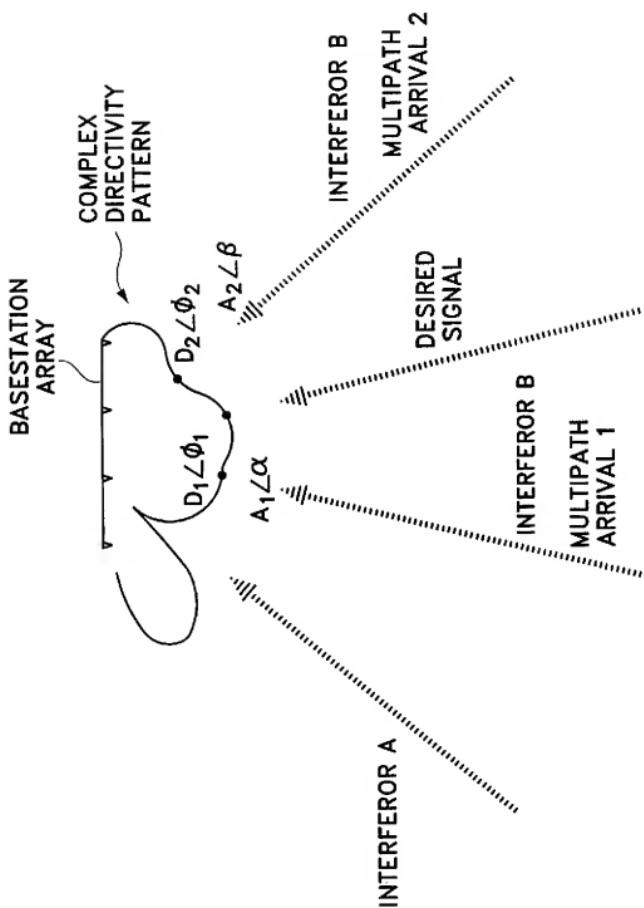


FIG. 26

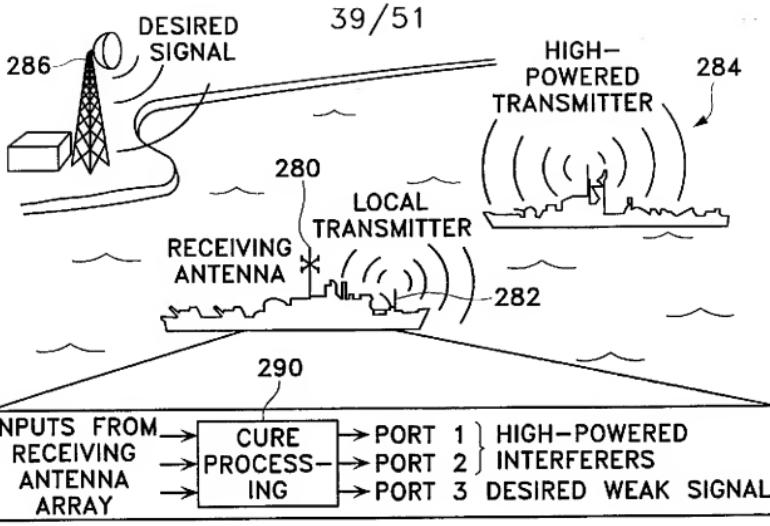
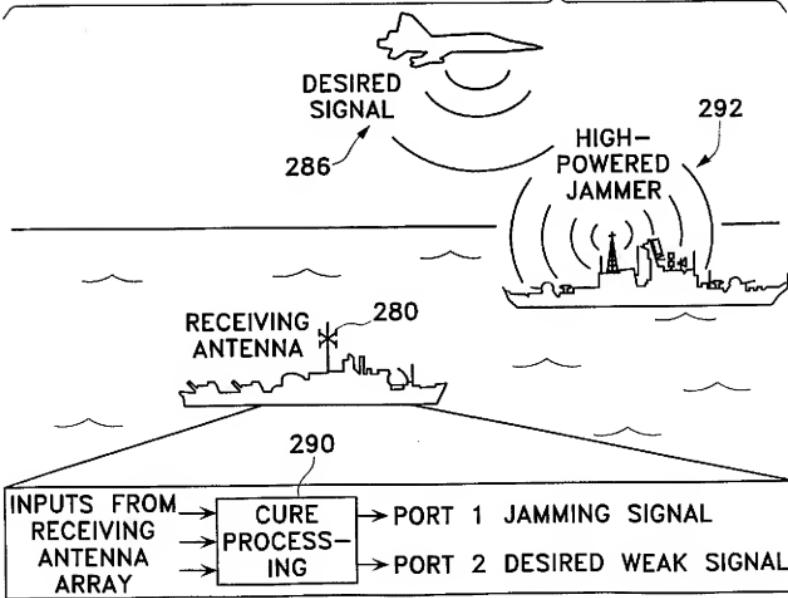


FIG. 27

FIG. 28



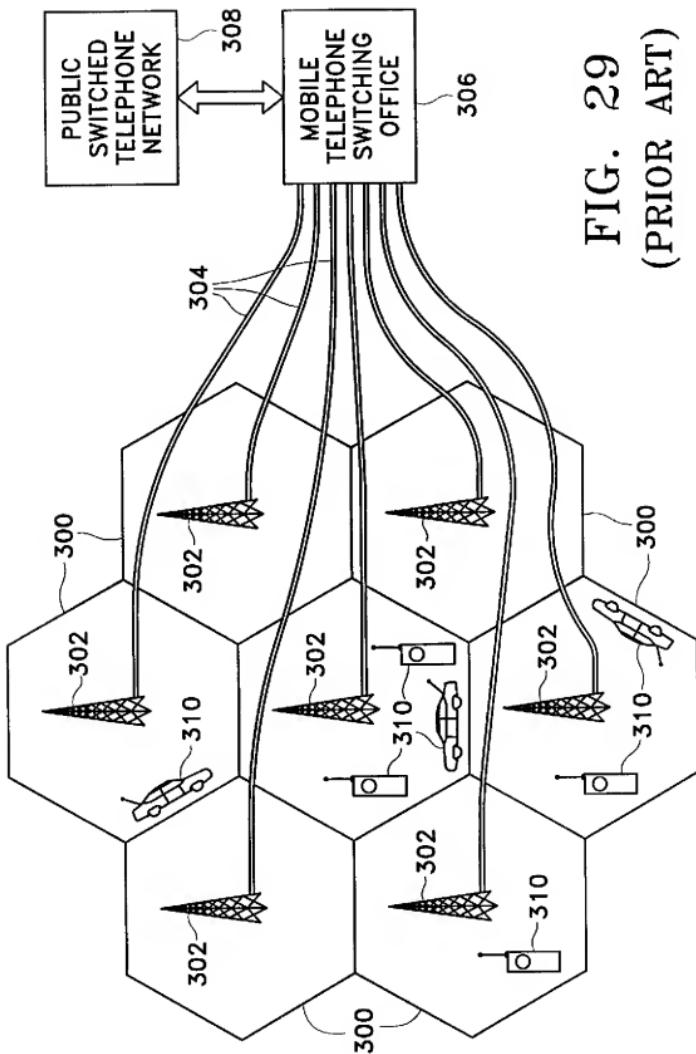
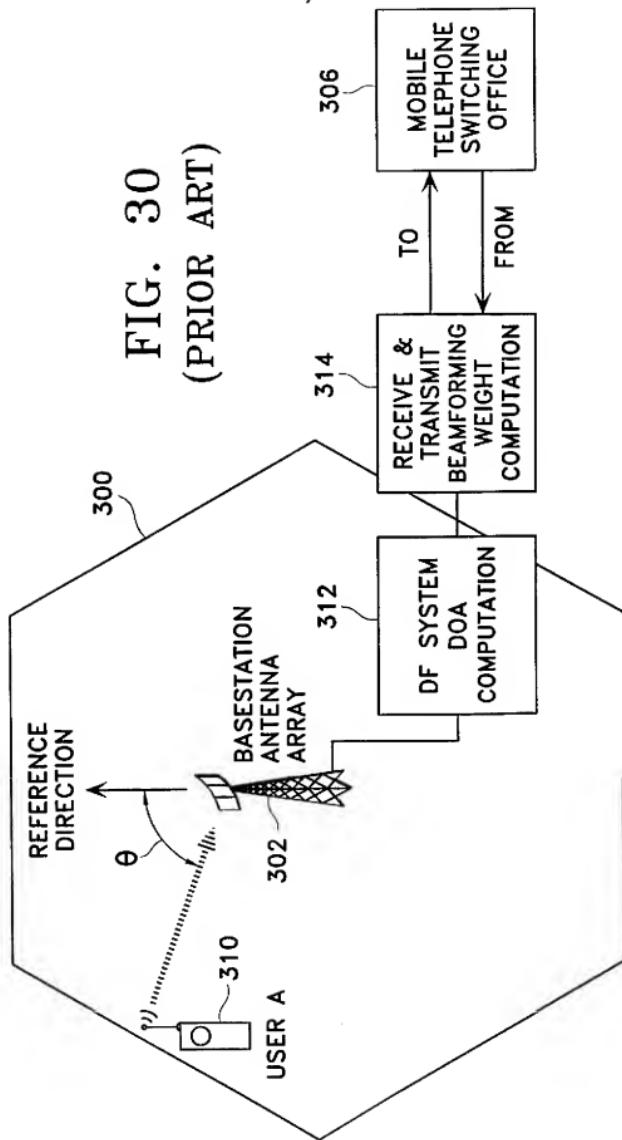


FIG. 29  
(PRIOR ART)

FIG. 30  
(PRIOR ART)



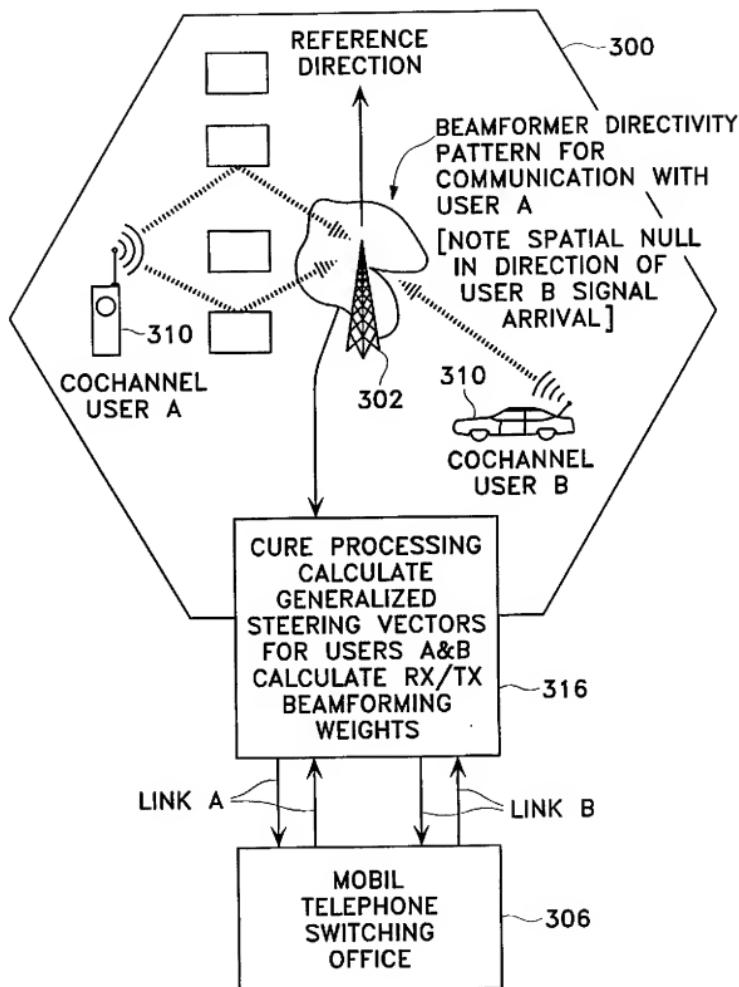


FIG. 31

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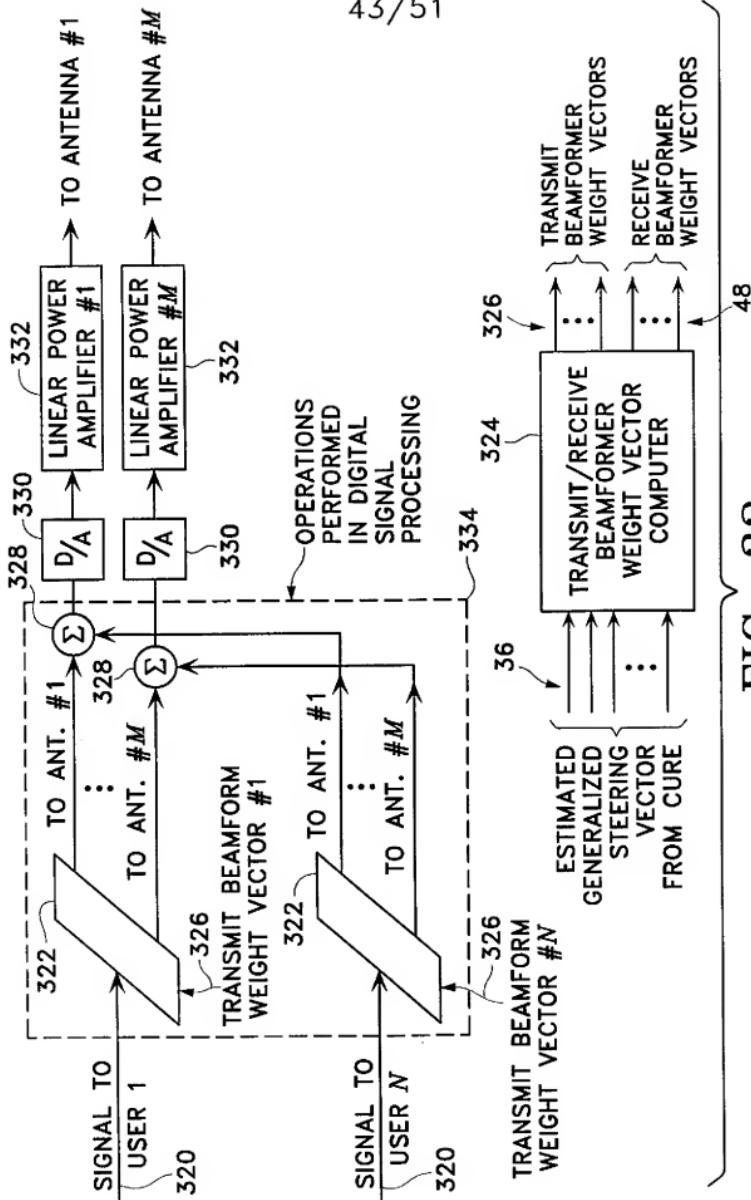
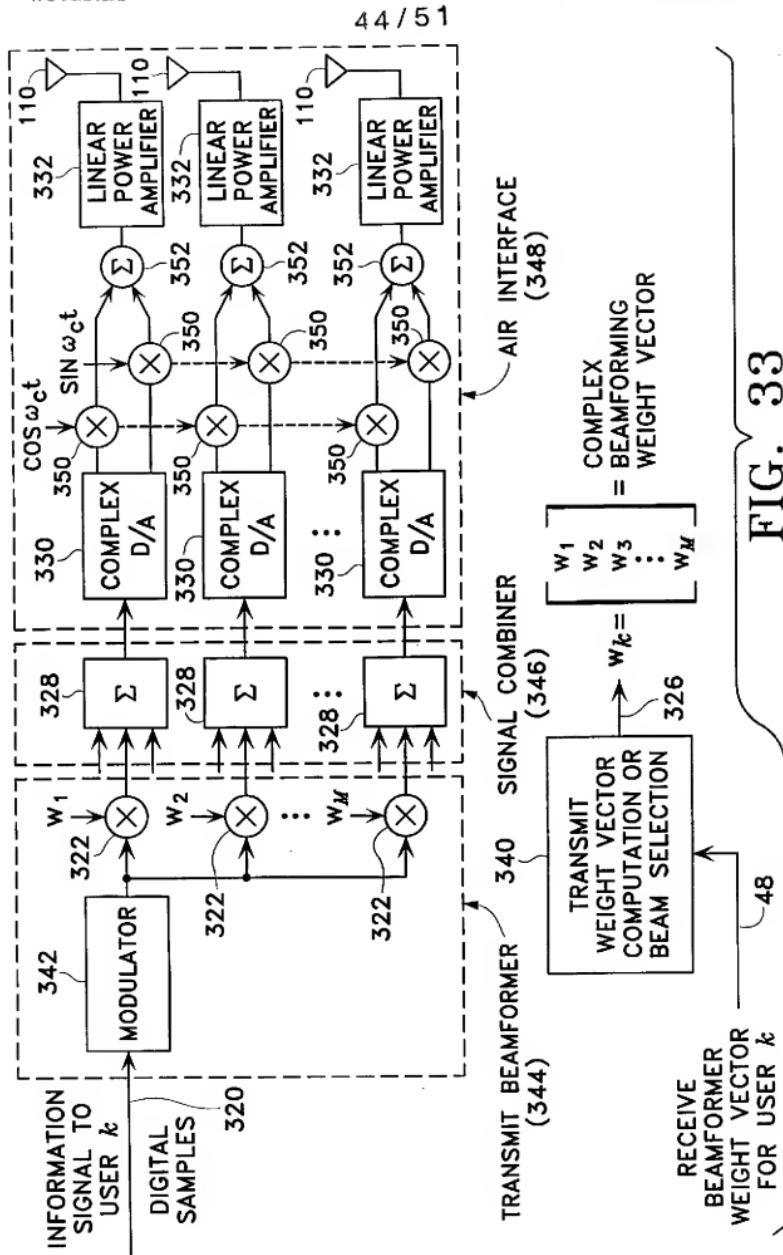


FIG. 32



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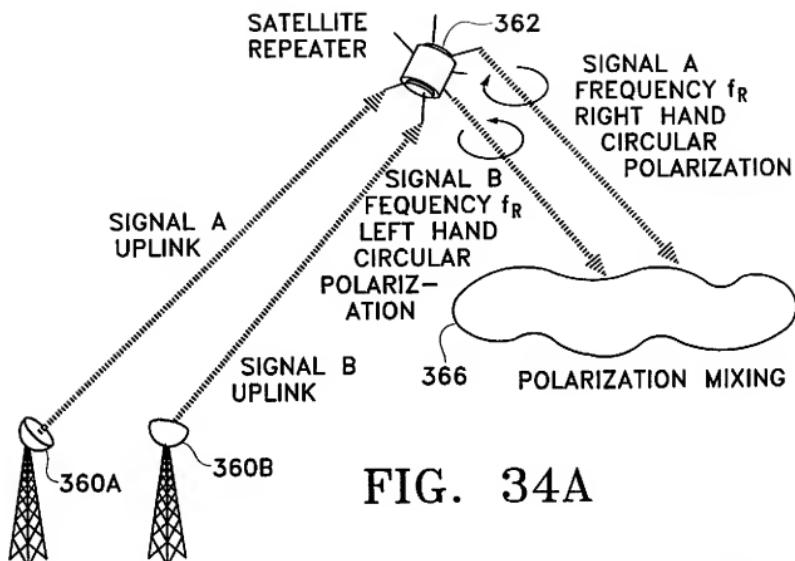


FIG. 34A

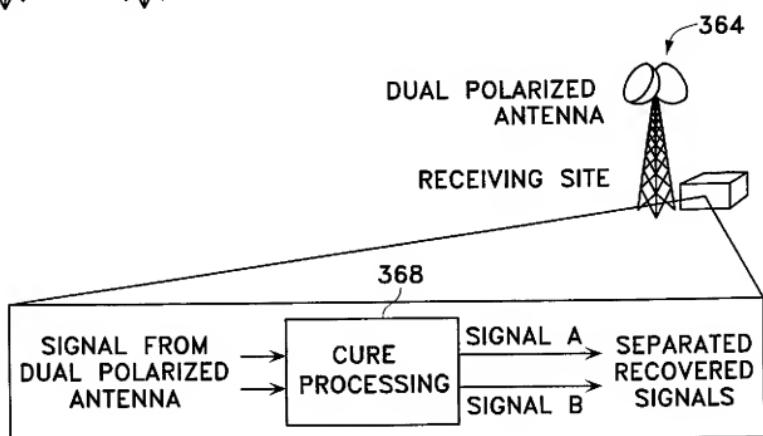


FIG. 34B

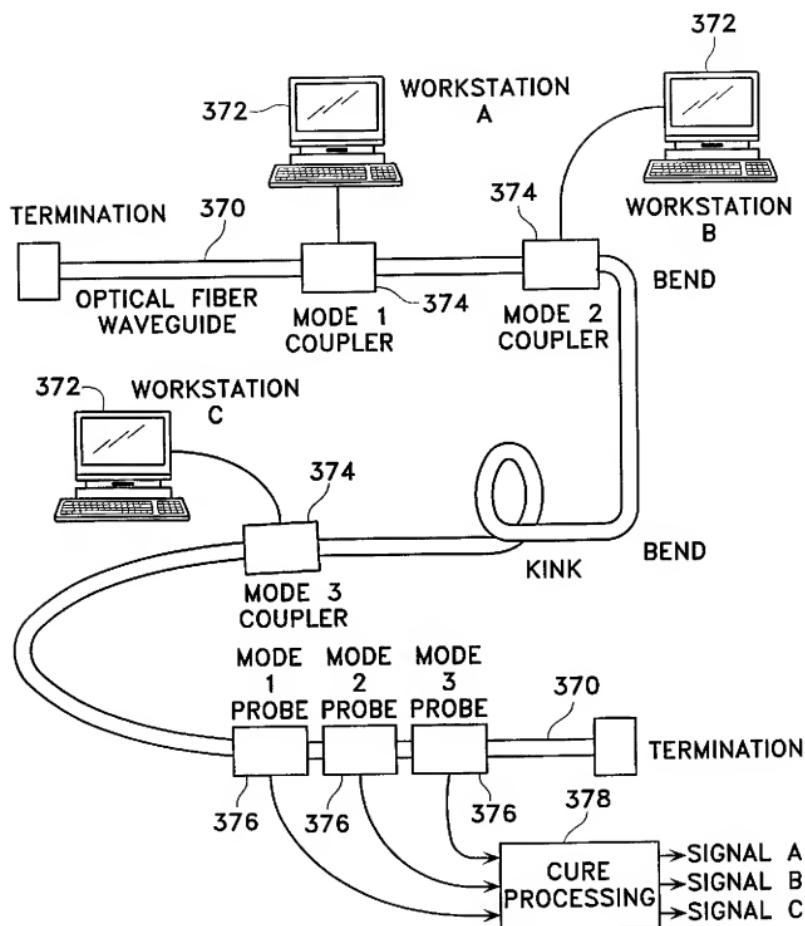


FIG. 35

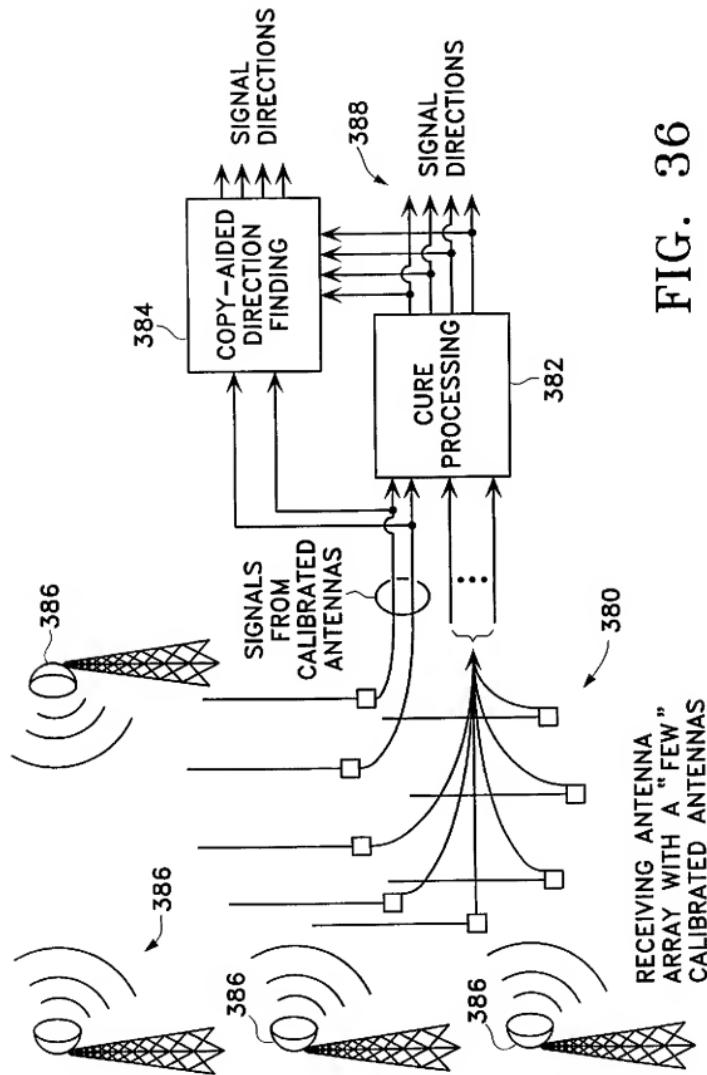


FIG. 36

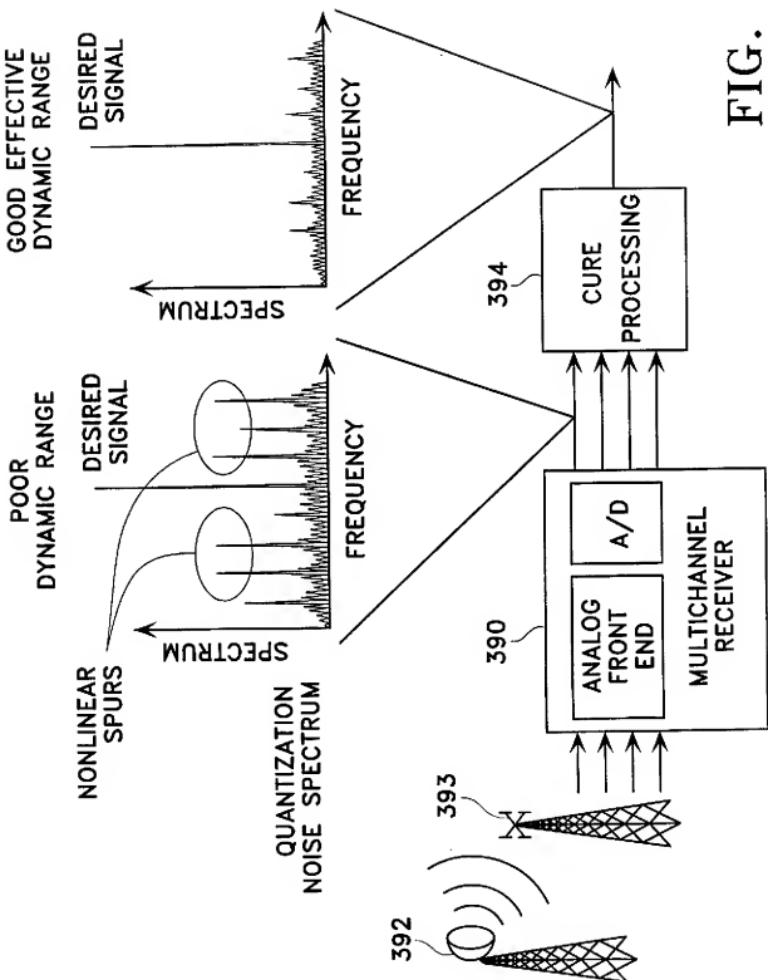
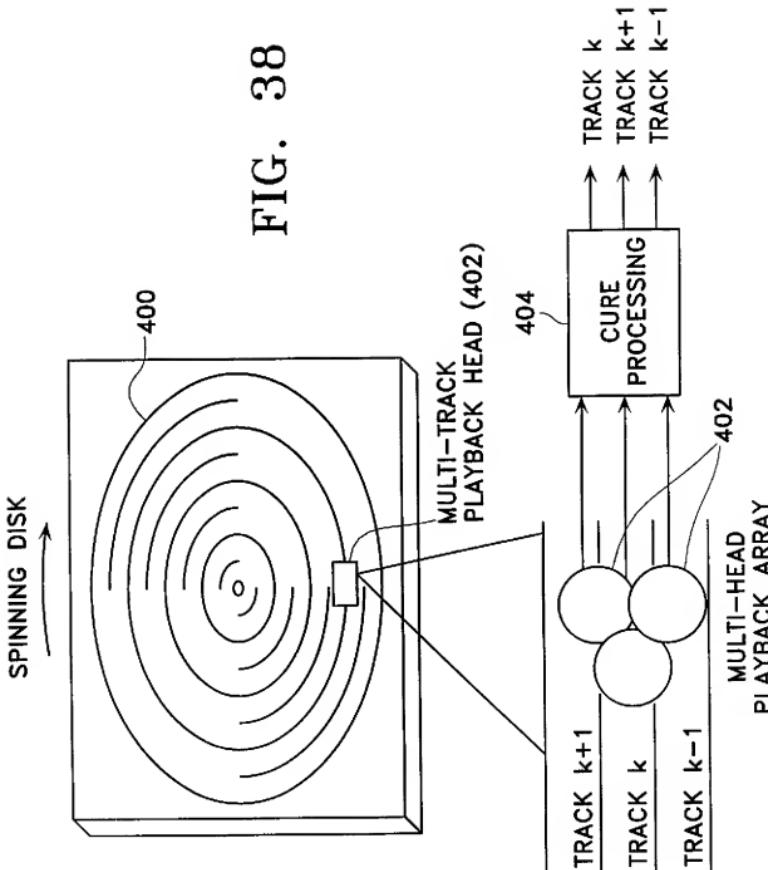


FIG. 37

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FIG. 38



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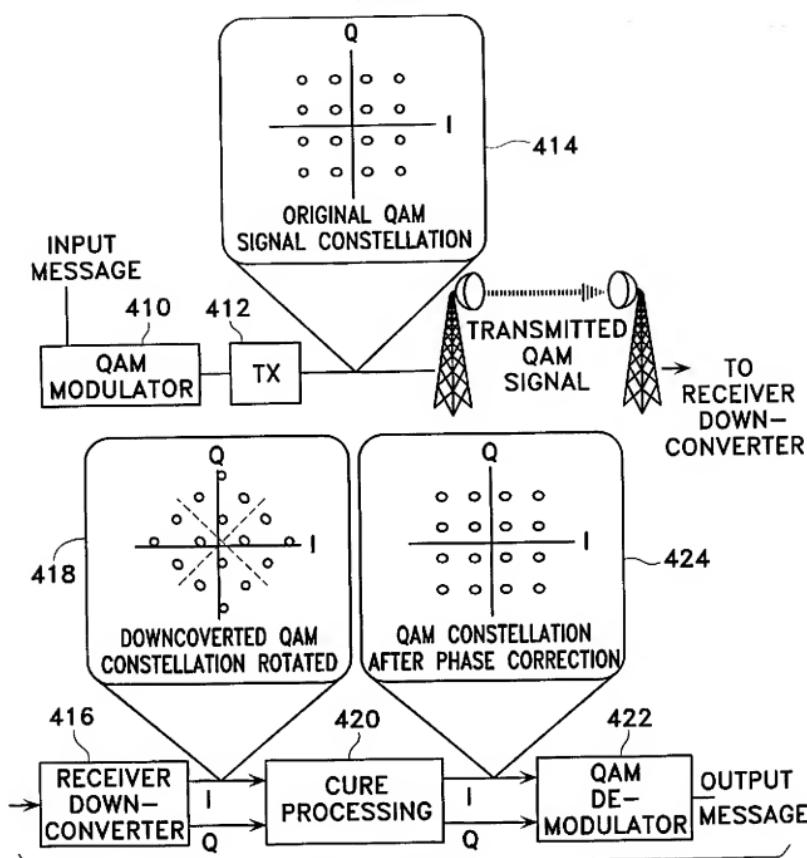
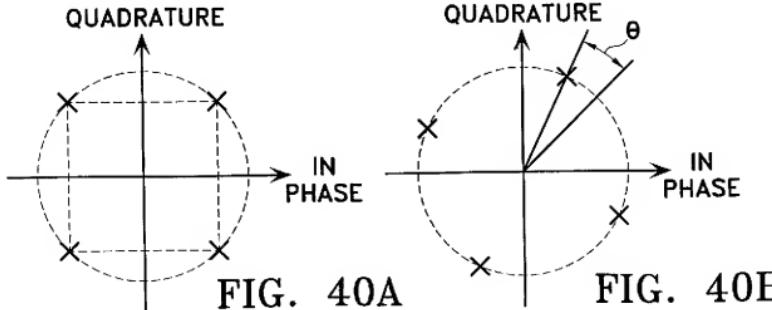


FIG. 39



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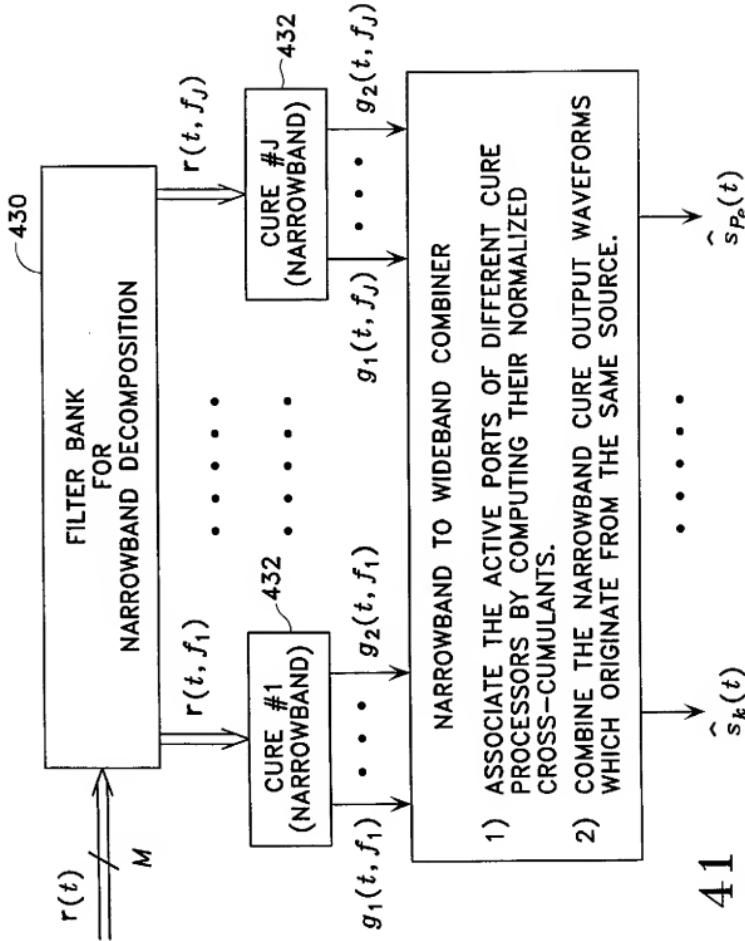


FIG. 41

## INTERNATIONAL SEARCH REPORT

Internal Application No  
PCT/US 96/18867A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 H04B7/08

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification systems followed by classification symbols)  
IPC 6 H04B G01S H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 565 479 A (UNIV RAMOT) 13 October 1993 see page 2, line 22 - line 35 see page 5, line 13 - line 27 see page 8, line 4 - page 10, line 31 see claim 1 ---	1,30,59, 69,74,92
A	US 5 315 532 A (COMON PIERRE) 24 May 1994 see column 1, line 11 - column 2, line 23 see column 2, line 46 - column 3, line 9 see column 3, line 32 - column 4, line 11 see column 5, line 37 - column 7, line 18 ---	1,30,59, 69,74,92
A	US 5 515 378 A (ROY III RICHARD H ET AL) 7 May 1996 see column 16, line 27 - line 35 see column 22, line 23 - line 54 -----	1,30,59, 69,74,92



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

## \* Special categories of cited documents :

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

- \*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- \*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- \*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- \*Z\* document member of the same patent family

Date of the actual completion of the international search

25 July 1997

Date of mailing of the international search report

20.10.97

Name and mailing address of the ISA

European Patent Office, P B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel: (+31-70) 340-2040, Tx. 31 851 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

BOSSEN, M

# INTERNATIONAL SEARCH REPORT

Int'l. application No.

PCT/US 96/18867

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:
2.  Claims Nos.: because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3.  Claims Nos.: because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see extra sheet

1.  As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2.  As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3.  As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
4.  No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-84,92

### Remark on Protest

The additional search fees were accompanied by the applicant's protest.

No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

International Application No. PCT/US 96 18867

## FURTHER INFORMATION CONTINUED FROM PCT/ISA210

1. claims 1-84,92: signal processing for separating co-channel signals from multiple sources received at a sensor array
2. claims 85,86: cumulant-based signal processing of signals received at an antenna array to eliminate effects of modification of signals during radio propagation
3. claims 87-89: signal processing for separating signals transmitted over a electromagnetic waveguide and received at an array of probes
4. claim 90: method for increasing the capacity of a communication system by separating the signals of N users (sharing the same bandwidth) received on an M-element antenna array
5. claim 91: signal processing for separating interference signals from a desired signal received at an antenna array
6. claims 93: method for extending the effective dynamic range of a radio receiver system by eliminating distortion products created as a result of analog-to-digital conversion of a signal received through an antenna array
7. claims 94,95: signal processing for separating data recorded on adjacent tracks on a recording medium
8. claims 96,97: complex phase equalization of I and Q components of a received and downconverted signal in which the I and Q signals are processed by the use of cumulant statistics in order to obtain phase correction of the I and Q signals prior to demodulation

## INTERNATIONAL SEARCH REPORT

Information on patent family members

Internal Application No

PCT/US 96/18867

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0565479 A	13-10-93	IL 101556 A JP 6021838 A US 5539832 A	04-08-96 28-01-94 23-07-96
US 5315532 A	24-05-94	FR 2657173 A DE 69011535 D DE 69011535 T EP 0511240 A WO 9111037 A JP 5503993 T	19-07-91 15-09-94 09-02-95 04-11-92 25-07-91 24-06-93
US 5515378 A	07-05-96	AU 670766 B AU 3145493 A CA 2125571 A EP 0616742 A FI 942771 A JP 7505017 T WO 9312590 A US 5546090 A US 5625880 A US 5592490 A US 5642353 A	01-08-96 19-07-93 24-06-93 28-09-94 10-06-94 01-06-95 24-06-93 13-08-96 29-04-97 07-01-97 24-06-97



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(54) Title: OPTIMAL USE OF LOGICAL CHANNELS WITHIN A MOBILE TELECOMMUNICATIONS NETWORK			
(57) Abstract			
<p>A broadcast message indicating the utilization level associated with Stand-alone Dedicated Control Channels (SDCH) within a mobile telecommunications network serving a particular geographic area is transmitted over a broadcast channel. A plurality of mobile stations located within that particular geographic area monitoring the broadcast channel then receives the transmitted message. Thereafter, a mobile service request with a lower priority level than the indicated status level is queued by the associated mobile station and delayed until the channel utilization level descends to a network acceptable level.</p>			

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OPTIMAL USE OF LOGICAL CHANNELS WITHIN A MOBILE  
TELECOMMUNICATIONS NETWORK

BACKGROUND OF THE INVENTION

5           Technical Field of the Invention

The present invention relates to a telecommunications network and, in particular, to the efficient management of channel resources within a digital mobile communications network.

10           Description of Related Art

The general name of the connection between a particular mobile station traveling within a particular cell area and the base transceiver station (BTS) providing radio coverage for that particular cell area is the "radio interface" or "air interface". Historically, the communications of information across the air interface between a base transceiver station (BTS) and a mobile station has employed, so-called, analog modulation techniques. For example, Frequency Division Multiple Access (FDMA) technology has been widely utilized to assign each mobile station to one of a plurality of the frequency channels associated with the current cell area to communicate with the serving BTS. More recently, however, digital modulation techniques have been used in order to enhance the spectrum efficiency with which the bandwidth allotted to mobile communications is used. As an illustration, the two techniques of time division multiple access (TDMA) and code division multiple access (CDMA) have been utilized to allow communications to proceed between a BTS and a plurality of different mobile stations on a relatively limited amount of radio frequency bandwidth. The Global System for Mobile (GSM) communications system, for example, utilizes the TDMA concept with the allocation of one TDMA frame per carrier frequency channel to communicate between a mobile station and a BTS. Each frame is further subdivided into eight

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time-slots (TS). Each time-slot of a TDMA frame on a single frequency channel is referred to as a physical channel. Accordingly, there are eight physical channels per carrier in the GSM system. Each physical channel of the GSM system can be compared with one single channel in an FDMA-system, where every user is connected to the system via one of the associated frequencies.

The implementation of TDMA technology requires that a great quantity and variety of information must be transmitted between the serving BTS and the mobile station over the limited physical channels. For example, control data, service request data, actual traffic data, supplementary data, etc., have to be communicated over the physical channels. As a result, in order to distinguish one type of data from another, different logical channels have been named and mapped (assigned) on to the available physical channels. For example, actual speech is sent on the logical channel named "traffic channel ("TCH)" occupying one or more physical channels. Paging of a called party mobile station is performed over the logical "paging channel (PCH)" while synchronization of a mobile station with a serving BTS is performed over the logical "synchronization channel (SCH)" which occupies one of the physical channels. Accordingly, depending on the type of information being transmitted, different logical channels are utilized. Needless to say, if more physical channels are assigned to a particular logical channel, a lesser number of physical channels are available for the rest of the logical channels.

Because of the limited physical channel resources, mobile service providers are often faced with channel resource management and dimensioning problems. One such problem includes effectively managing Stand-alone Dedicated Control Channels (SDCCH) within a serving mobile network. Because of the fact that congestion in SDCCH logical channels results in lost calls and unsuccessful call setups, the efficient management of SDCCH logical

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channels is critical for providing reliable mobile service to mobile stations traveling within the serving coverage area.

SDCCH logical channels are not only utilized for setting up call connections, but also for performing location updates for traveling mobile stations and for communicating packet messages containing text or graphic data between the serving mobile network and associated mobile stations. Conventionally, all of the above mentioned functionalities are provided the same priority and allowed equal access to available SDCCH channel resources. As a result, all of the available SDCCH channel resources could be occupied by Short Message Service (SMS) or Unstructured Supplementary Service Data (JSSD) messages transporting text messages and could, as a result, prevent speech connections from being established between mobile stations and a serving mobile network. However, even though the support of all of the above mentioned functionalities is important for providing reliable and comprehensive mobile service to associated mobile stations, establishing call connections is by far the most important role performed by the mobile network.

Accordingly, there is a need for a mechanism to prioritize mobile services within a serving mobile network to better utilize available SDCCH logical channels.

#### SUMMARY OF THE INVENTION

The present invention discloses a method and apparatus for optimizing the utilization of Stand-alone Dedicated Control Channels (SDCCH) within a mobile telecommunications network for high priority mobile services. The level of utilization of SDCCH logical channels is maintained within a particular base station controller (BSC) serving a particular geographic area. After determining that such a level has exceeded a threshold value imposed by the serving telecommunications network, the BSC transmits data over a Broadcast Control

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Channel informing associated mobile stations traveling within its coverage area of such a determination. Thereafter, mobile stations wanting to request low priority mobile services are instructed to delay 5 requesting one of the available SDCCH logical channels until the utilization level falls below the imposed threshold level. As a result, available SDCCH logical channels remain available for high priority mobile services within a congested mobile telecommunications 10 network.

#### BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the method and apparatus of the present invention may be had by reference 15 to the following detailed description when taken in conjunction with the accompanying drawings wherein:

FIGURE 1 is a block diagram of a mobile telecommunications network illustrating a mobile station communicating with a serving base transceiver station 20 (BTS);

FIGURE 2 is a block diagram of physical channels allocated in accordance with the Time Division Multiple Access (TDMA) technology;

FIGURE 3 is a block diagram of different logical 25 channels within a TDMA physical frame in accordance with the Global System for Mobile (GSM) standard;

FIGURE 4 is a signal sequence diagram illustrating the communication of different messages for originating an outgoing call connection;

FIGURE 5 is a block diagram of a serving mobile 30 network transmitting Stand-alone Dedicated Control Channel (SDCCH) status information to a mobile station in accordance with the teachings of the present invention; and

FIGURE 6 is a flow-chart illustrating the steps 35 performed by a mobile station to request mobile service towards a serving mobile network.

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DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a Public Land Mobile Network (PLMN) 10 illustrating a mobile station 20 communicating with a serving base transceiver station (BTS) 30. A geographic area associated with a particular Public Land Mobile Network (PLMN) 10 is partitioned into a number of smaller areas. Whenever a mobile station 20 travels into one of those smaller areas known as a "location area", the mobile station performs a location update with the serving PLMN. Such a location update informs the associated mobile switching center / visitor location register (MSC/VLR) 50 of the mobile station's presence. In case the mobile station 20 is an unregistered subscriber, a home location register (HLR) 60 associated with the newly registering mobile station 20 is identified and necessary communication is facilitated between the serving MSC/VLR 50 and the HLR 60 to authenticate the new mobile station 20. Requisite subscriber information related to the newly registering mobile station 20 is further requested and retrieved from the associated HLR 60 and stored at the serving MSC/VLR 50. Thereafter, the mobile station 20 is allowed to access mobile service within the serving MSC/VLR 50 coverage area.

Whenever an incoming call connection is requested towards the mobile station 20, a call setup signal, such as an Integrated Service Digital Network User Part (ISUP) based Initial Address Message (IAM) is received by a gateway mobile switching center (GMSC) 80 associated with the HLR 60. After performing HLR interrogation to ascertain the current location of the mobile station 20, the received incoming call setup signal is rerouted by the GMSC 80 to the MSC/VLR 50 currently serving the mobile station 20. The MSC/VLR 50 then determines the current location area of the mobile station 20 and instructs the appropriate base station controller (BSC) 40 to page the mobile station 20. The BTS 30 then pages the mobile

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station to alert the mobile station of an incoming call. As soon as the mobile station detects the paging message, the mobile station 20 sends a request for a signaling channel to the BSC 40. After allocating an idle signaling 5 channel to the mobile station 20, the BSC 40 sends a message instructing the mobile station 20 to switch to that particular signaling channel. After communicating necessary control and service related data over the newly allocated signaling channel, a speech channel is 10 subsequently seized and a call connection between the mobile station 20 and the BSC 40 is established via the BTS 30.

Initially, the communication interface 90 between the serving BTS 30 and the mobile station 20 employed so 15 called analog modulation techniques. However, with the recent developments of digital communication technology, digital modulation techniques are being used to enhance the efficiency and capacity of data communications within a mobile telecommunications network. As an illustration, 20 the techniques of time division multiple access (TDMA) or code division multiple access (CDMA) are being used to allow multiple communications to proceed on a relatively limited amount of radio frequencies. Global System for 25 Mobile (GSM) based telecommunications networks, for example, utilize the TDMA technology with one TDMA frame per carrier frequency to communicate between a mobile station and a BTS.

Reference is now made to FIG. 2 depicting a 30 diagrammatic representation of time-frame structures within the GSM standard. The longest recurrent time period of the structure is called a hyperframe 100 and has the duration of 3 hours 28 minutes 53 seconds 760 ms. One hyperframe 100 is divided into 2048 superframes 105, each having a duration of 6.12 seconds. The superframe 105 is 35 itself sub-divided into a number of multiframe. Two types of multiframe exist in the GSM standard. First, there is a fifty-one (51) frame multiframe 110 with a

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duration of 120 ms, comprising twenty-six (26) TDMA frames 130. Next, there is a twenty-six (26) frame multiframe 120 with a duration 235.4 ms, comprising fifty-one (51) TDMA frames 140. Lastly, each TDMA frame within a 5 multiframe has eight time slots 150. Each of these eight physical time slots is equivalent to one Frequency Division Multiple Access (TDMA) channel serving a single mobile station.

10 A great quantity and variety of information must be transferred between the BTS and the mobile station. For example, paging to inform the mobile station of an incoming call has to be performed over one of the time slots. A request for mobile service further needs to be communicated over one of the time slots. Furthermore, the 15 actual voice data must be communicated over the available time slots. Therefore, in order to distinguish one type of information over another, different logical channels have been introduced and assigned to each of the eight physical time slots.

20 Reference is now made to FIG. 3 illustrating different logical channels within the GSM standard which can be separated into two broad categories: traffic channels (TCH) 160 and signaling channels 170. Traffic channels (TCH) 169 are utilized by the serving BSC to 25 communicate call data (e.g., voice data) with a particular mobile station traveling within its coverage area. On the other hand, signaling channels 170 are utilized by the serving BSC and BTS to communicate other control data necessary to implement the communication of call data with 30 the mobile station.

35 Signaling channels are further subdivided into three categories: broadcast control channels 270, common control channels 280, and dedicated control channels 280. Each of the above three categories are then still further subdivided into a number of logical channels for transporting different types of information between the serving BTS and the mobile station.

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Broadcast control channels 270 are mainly utilized for communicating information from the serving BTS to a particular mobile station traveling within its coverage area (down-link) and include the Frequency Correction Channel (FCCH) 180, Synchronization Channel (SCH) 190, and Broadcast Control Channel (BCCH) 200. The Frequency Correction Channel (FCCH) 180 carries information for frequency correction of the mobile station. The Synchronization Channel (SCH) 190 carries information for frame synchronization of the mobile station and identification of the BTS. Lastly, the Broadcast Control Channel (BCCH) 200 is used to broadcast general system information about the cell to all mobile stations located within its location area. For example, the broadcast system information includes data about the network that the mobile station needs to be able to communicate with the network in an appropriate manner. Such information includes cell description, location area identity, neighbor cell description, etc.

Common control channels 280 include the Paging Channel (PCH) 210, Random Access Channel (RACH) 220, and Access Grant Channel (AGCH) 230. The Paging Channel (PCH) 210 is used on the downlink to page a mobile station. For example, when an incoming call setup request is received by the serving MSC/VLR, the appropriate BSC currently serving the mobile station is instructed to page the specified mobile station over a PCH. The Random Access Channel (RACH) 220, on the other hand, is used by the mobile station to request allocation of a Stand-alone Dedicated Control Channel (SDCCH) 240 to the BSC. For example, upon detecting the paging message informing the mobile station of an incoming call, the called party mobile station requests a SDCCH from the serving BSC over a RACH. After allocating an idle SDCCH, the BSC utilizes an Access Grant Channel (AGCH) 230 to communicate the identity of the allocated SDCCH to the requesting mobile station.

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Dedicated control channels 290 include the Stand-alone Dedicated Control Channel (SDCCH) 240, Slow Associated Control Channel (SACCH) 250, and the Fast Associated Control Channel (FACCH) 260. The Stand-alone 5 Dedicated Control Channel (SDCCH) 240 is used for signaling with a dedicated mobile station. Accordingly, the SDCCH 240 is the channel used for performing location update procedures whenever a mobile station enters a new location area. The SDCCH is also utilized to initiate a 10 call setup and to seize a TCH. Furthermore, SDCCH logical channels are utilized by the serving mobile network to communicate Unstructured data, such as Short Message Service (SMS) or Unstructured Supplementary Service Data (USSD) messages with associated mobile stations. The Slow 15 Associated Control Channel (SACCH) 250 is associated with a TCH 160 or an SDCCH 240. The SACCH 250 is a continuous data channel carrying continuous control information, such as measurement reports, timing advance and power order, between the serving BSC and the mobile station. Lastly, 20 the Fast Associated Control Channel (FACCH) 260 is associated with a particular TCH to work in burst stealing mode to replace speech or data traffic with other necessary signaling.

As illustrated above, with nine different types of 25 logical signaling channels and one logical traffic channel occupying the limited physical channels, the eight time slots within a TDMA frame need to be managed efficiently and effectively to provide reliable mobile service to mobile stations traveling within a particular BSC coverage 30 area. Since logical channel assignments to physical channels can not be changed dynamically as demands for each logical channel changes within a serving network, determining the appropriate number of physical time slots to be assigned to each of the logical channels is crucial. 35 Especially since congestion in the two of the most frequently utilized logical channels (SDCCH and TCH) results in failed call connection and lost calls.

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Therefore, even after allocating an appropriate number of physical channels to each logical channel, efficient management of channel resources is further necessary to maximize the potential utilization of available logical channels.

FIG. 4 is a signal sequence diagram illustrating a normal call setup procedure in accordance with the GSM standard. Whenever a mobile station 20 requests mobile service towards the serving mobile switching center (MSC) 50, either for originating an outgoing call connection or for receiving an incoming call connection, the mobile station 20 transmits a channel request message over a Random Access Channel (RACH) towards the connected BSC 40. After communicating with the associated MSC 50, an available SDCCH channel is allocated. The serving BSC 40 then transmits an Immediate Assignment Command message 310 to the serving BTS 30 (not shown in FIG. 4) to assign the allocated SDCCH to the requesting mobile station 20. The Immediate Assignment message 310 is further transmitted to the requesting mobile station 20 to instruct the mobile station 20 to switch to the assigned SDCCH. Utilizing the assigned SDCCH logical channel, the mobile station 20 requests mobile service from the serving MSC 50 by transmitting a Ciphering Mode Service Request(CM Serv. Req.) message 320. The serving BSC 40 then sets up an Signaling Connection Control Part (SCCP) connection with the MSC 50 by transmitting a SCCP - Connection Request (CR) message 330. The received CM-SERV. REQ. message 320 may further be "piggy-backed" to the transmitted SCCP-CR message 330. The serving MSC 50 is then aware of the mobile station's request for mobile service. As a result, the MSC 50 attempts to authenticate the mobile station 20 by transmitting an Authentication Request message 350 to the mobile station 20 transparently through the connected BSC 40 and over the assigned SDCCH logical channel. The mobile station 20, in response, attempts to comply with the authentication process by returning an Authentication

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Response message 360 to the serving MSC 50. If the authentication procedure is successfully performed, the ciphering mode setting procedure may be initiated by the serving MSC 50. Accordingly, the serving MSC 50 sends a 5 Ciphering Mode Command (not shown in FIG. 4) to BSC 40. The BSC 40, in turn, transmits a Ciphering Mode Command message 370 including a cipher key to the mobile station 20 over the assigned SDCCH logical channel. The provided cipher key is then later utilized by the serving BSC and 10 the mobile station to cipher and decipher digital data transmitted over the radio interface. After storing the received cipher key, the mobile station 20 returns a Ciphering Mode Complete message 380 to the serving BSC 40 over the assigned SDCCH logical channel. The received 15 Ciphering Mode Complete message 390 is then transmitted to the serving MSC 50. Furthermore, in order to guarantee the mobile subscriber's confidentiality, instead of identifying the mobile station with its permanently assigned International Mobile Subscriber Identity (IMSI) 20 number, a Temporary Mobile Subscriber Identity (TMSI) number is further assigned by the serving MSC 50. The assigned TMSI number is then included in a TMSI Reallocation Command message 400 and transmitted to the mobile station 20 over the assigned SDCCH logical channel. 25 The mobile station 20 then confirms the receipt of the assigned TMSI number by transmitting a TMSI Reallocation Complete message 410 over the assigned SDCCH logical channel back to the serving MSC 50. The mobile station 20 is now prepared to originate an outgoing call 30 connection and transmits a Call Setup message 420 towards the serving MSC 50. The transmitted Setup message 420, for example, includes the directory number associated with the intended called party subscriber. The serving MSC 50 then acknowledges the call setup signal by transmitting 35 a Call Confirmation message 430 back to the requesting mobile station 20 over the assigned SDCCH logical channel. The BSC 40 then selects an idle traffic channel (TCH) and

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instructs the mobile station 20 to tune to the newly allocated TCH logical channel by transmitting an Assignment Command message 440 over the SDCCH logical channel. As an acknowledgment, the mobile station 20  
5 returns an Assignment Complete message 450 back to the serving MSC 50 indicating that the traffic channel is up and running. The BSC then releases the no-longer-needed SDCCH logical channel. An Alert message 460 is then transmitted from the serving BSC 40 to the mobile station  
10 20 informing the mobile station that a ringing tone has been generated by the serving MSC 50. Thereafter, a Connect signal 470 is transmitted from the mobile station 20 to the serving MSC 50. The serving MSC 50 then  
15 acknowledges the connect signal by returning a Connect Acknowledgment message 480 to the requesting mobile station 20. Thereinafter, speech connection is established over the newly allocated TCH logical channel allowing the mobile station 20 to communicate data (e.g., voice) with its called party subscriber.

20 It is to be understood that the call originating procedure illustrated above is for exemplary purposes only and that call termination procedures for an incoming call setup are also applicable in the sense that the SDCCH is also needed and extensively utilized before a call can be  
25 terminated towards its called party mobile station.

As illustrated above, until a TCH logical channel is seized enabling a mobile subscriber to communicate with another telecommunications terminal, a great variety and quantity of information needs to be exchanged between the serving mobile network and the requesting mobile station over a SDCCH logical channel. Such information includes authentication data, channel assignment data, service request data, TMSI number data, and call setup information data. Accordingly, without an available SDCCH channel, even if a TCH logical channel is available, a mobile station is not able to access mobile service. Such mobile service includes not only call setup requests as explained  
30  
35

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above but a number of other functionalities. Each time a mobile station travels into a new location area being served by a new BSC, the traveling mobile station needs to perform a location update with its associated home 5 location register (HLR) over a SDCCH logical channel. Periodically, the mobile station then has to inform the serving BSC and MSC that the mobile station is still within the service area by performing International Mobile Subscriber Identity (IMSI) Attach procedures over SDCCH 10 logical channels. Terminating call connections, in a manner similar to as described above, also need SDCCH logical channels to alert mobile stations and to establish terminating call connections. Furthermore, unstructured data, such as Short Message Service (SMS) and Unstructured 15 Supplementary Service Data (USSD) messages are also communicated over SDCCH logical channels. With all of the above described mobile services attempting to seize and utilize a limited number of SDCCH logical channels within a particular mobile telecommunications network, providing 20 efficient and effective SDCCH logical channel resource management becomes crucial for providing reliable and efficient mobile service to associated mobile stations.

Reference is now made to FIG. 5 illustrating a serving mobile network transmitting Stand-alone Dedicated 25 Control Channel (SDCCH) status information to a mobile station in accordance with the teachings of the present invention. A telecommunications node associated with a particular geographic area, such as a cell area, maintains statistical data representing the utilization level of 30 SDCCH logical channels associated with that particular area. Such a telecommunications node may comprise a base station controller (BSC) 60 serving that particular geographic area. It may further comprise a base transceiver station (BTS) serving that particular cell 35 area. Each time a SDCCH channel is requested and allocated by one of the associated base transceiver station (BTS) 30 for a particular mobile station, the

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statistical data associated with that particular cell area is updated by an application module 500 associated with the BSC 60. Similarly, each time an allocated SDCCH logical channel is released by a mobile station, the 5 statistical data is updated to reflect the availability of the released channel within the geographic area.

In case the maintained statistical data reflecting the level of SDCCH utilization exceeds a threshold level imposed by the associated mobile telecommunications 10 network, indication is noted that the level of SDCCH utilization within the serving geographic area has reached an undesirable level and there are inadequate amount of available SDCCH logical channels remaining to adequately handle potential high-level mobile service requests from 15 its associated mobile stations. As a result, the application module 500 transmits a broadcast message to all mobile stations located within its coverage area over one of its broadcast channels. In order to reach all mobile stations currently traveling within the effected 20 geographic area, the message may be transmitted over a Broadcast Control Channel (BCCH). The transmitted broadcast message indicates the over-utilization of SDCCH logical channel resources within the current geographic area and instructs the receiving mobile stations to delay 25 requesting low-level mobile service from the serving mobile network.

As another embodiment of the present invention, a plurality of threshold levels may be assigned to the serving mobile telecommunications network. As an 30 illustration, a first threshold level is assigned allowing access to all mobile services except the lowest level mobile services, such as SMS or USSD services. A second threshold level may further be assigned to restrict the next level of mobile service. For example, location updates and IMSI attach may further be restricted from 35 accessing the network. The highest threshold level may then be imposed to allow only access for call connections.

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Such a hierarchical structure of mobile services may be identified and determined by the service operator and freely associated with dynamically assignable threshold values. The serving BSC 60 then transmits an appropriate broadcast message informing the associated mobile stations with which level the current utilization level is currently associated.

Upon receiving such SDCCH status information, a mobile station wanting to request mobile service first determines whether the mobile service has higher priority than the received SDCCH status. If the desiring mobile service has lower priority than the current SDCCH resource status, an application module 510 within the mobile station 20 queues the received requests. An indication to the associated mobile subscriber that the requested mobile service is being queued and delayed may further be displayed. Thereafter, the mobile station 20 periodically monitors the BCCH logical channel to determine whether the SDCCH utilization level has been reduced enough to allow access to the mobile network. Such a determination can be made by a number of ways. A different broadcast message may be transmitted by the serving BSC 60 notifying the mobile stations traveling within its effective area that the SDCCH utilization level has decreased. As an alternative, if the monitoring mobile stations no longer receives broadcast messages over the BCCH logical channel, a presumption is then made by the application module 510 that the restriction on the SDCCH channel request is no longer valid. The application module 510 then retrieves the previously queued request and the retrieved mobile service request is then performed in a conventional manner.

Reference is now made to FIG. 6 illustrating the steps performed by a mobile station to comply with the SDCCH resource management procedure in accordance with the teachings of the present invention. A broadcast channel, such as the Broadcast Control Channel (BCCH), is

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periodically monitored by the mobile station current located within the particular geographic area at step 500. Thereafter, the mobile station receives an indication to request mobile service towards the serving mobile network.

5        Such an indication may include an associated subscriber entering a directory number, service codes or function keys. Moreover, such an indication may be generated and detected internally within the mobile station. Furthermore, such mobile service may include originating

10      an outgoing call connection, transmitting SMS or USSD messages, or performing location update. In response, an application module associated with the mobile station determines whether a broadcast message associated with the SDCCH resources has been received over the BCCH logical

15      channel. If no such status message has been received, the mobile station takes the "No" decision link 570 and performs the requested mobile service in a conventional manner at step 560. On the other hand, if such status information has been received over the broadcast channel,

20      the mobile station compares the priority of the requested mobile service with the received SDCCH resource status at step 520. If the mobile station is requesting a service higher than the SDCCH resource status currently indicated by the received broadcast message, the mobile station

25      takes the "No" decision link 590 and requests the mobile service in a conventional manner at step 560. If, however, the requesting mobile service has lower priority than the received channel resource status, the application module associated with the mobile station delay

30      transmitting the request by buffering or queuing the received request. Such a request may be queued within a Subscriber Identity Module (SIM) card associated with the mobile station.

35      Thereafter, the mobile station monitors the broadcast channel to determine whether the channel resource utilization level has decreased enough to enable the mobile station to request the queued mobile service. As

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described previously, such a determination can be made either by receiving a different broadcast message indicating a lower utilization level or by not receiving any broadcast message over a predetermined period of time.

5 As an illustration, if the same broadcast message restricting the mobile station from requesting low level mobile service is being transmitted over the BCCH logical channel, the mobile station awaits until the restricting message is no longer received at step 540.

10 After making a determination that the SDCCH utilization level has decreased, the mobile station then retrieves the previously queued mobile service at step 550. The retrieved mobile service is then requested in a conventional manner at step 560.

15 Accordingly, by enabling mobile stations to comply with transmitted broadcast messages, the serving mobile telecommunications network is able to better utilize valuable SDCCH logical channel resources for high priority mobile service when the SDCCH utilization has exceed an undesirably high level.

20 Although a preferred embodiment of the method and apparatus of the present invention has been illustrated in the accompanying Drawings and described in the foregoing Detailed Description, it will be understood that 25 the invention is not limited to the embodiment disclosed, but is capable of numerous rearrangements, modifications and substitutions without departing from the spirit of the invention as set forth and defined by the following claims.

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WHAT IS CLAIMED IS:

1. A method for communicating data reflecting the status of channel resources to a plurality of mobile stations within a mobile telecommunications network, said 5 method comprising the steps of:

maintaining a plurality of first channels for facilitating data communication between a telecommunications node serving said plurality of mobile stations and said plurality of mobile stations;

10 determining that the utilization of said plurality of first channels by some of said plurality of mobile stations has reached a threshold level associated with said telecommunications node; and

15 transmitting, in response to said determination, first data reflecting the status of said utilization of said plurality of first channels to said plurality of mobile stations over a second channel.

2. The method of claim 1 wherein said first data are 20 transmitted periodically until said utilization of said plurality of first channels has fallen below said threshold level.

3. The method of claim 1 further comprising the 25 steps of:

determining that said utilization of said plurality of first channels has fallen below said threshold level; and

30 transmitting second data reflecting the availability of said plurality of first channels to said plurality of mobile stations over said second channel.

4. The method of claim 1 wherein said 35 telecommunications node is associated with a plurality of threshold levels and wherein said step of determining further comprises the step of determining with which one of said plurality of threshold levels said utilization of

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said plurality of first channel is associated and wherein said transmitted first data further indicates with which one of said plurality of threshold levels said determined status is associated.

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5. The method of claim 1 wherein said first data further reflects the scarcity of said plurality of first channels and instructs said plurality of mobile stations to delay requesting low priority mobile services from said 10 telecommunications node.

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6. The method of claim 5 wherein said low priority mobile services include a Short Message Service (SMS).

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7. The method of claim 5 wherein said low priority mobile services include a Unstructured Supplementary Service Data (USSD) service.

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8. The method of claim 1 wherein said plurality of first channels comprise Stand-alone Dedicated Control Channels (SDCCHs).

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9. The method of claim 1 wherein said second channel comprises a Broadcast Control Channel.

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10. A method for optimizing the utilization of a plurality of first logical channels for a high priority mobile service within a mobile telecommunications network, said method comprising the steps of:

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receiving a first indication at a particular mobile station indicating the availability of said plurality of first logical channels within said mobile telecommunications network;

35

receiving a second indication to request a mobile service towards said telecommunications node at said mobile station;

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determining that said requested mobile service has lower priority in comparison to said availability of said plurality of first logical channels; and

5 delaying said request for said mobile service towards said telecommunications node in response to said determination.

10 11. The method of claim 10 wherein said first indication comprises data received over a Broadcast Control Channel.

15 12. The method of claim 10 wherein said first logical channels comprises Stand-alone Dedicated Control Channels (SDCCHs).

13. The method of claim 10 further comprising the steps of:

20 determining that current availability of said plurality of said first channels within said mobile telecommunications network is now able to handle said requested mobile service; and

requesting said mobile service towards said telecommunications node by requesting one of said plurality of said first logical channels.

25 14. A system for communicating data indicating the status of channel resources to a plurality of mobile stations within a mobile telecommunications network, said channel resources associated with a plurality of first logical channels for facilitating data communication between said plurality of mobile stations and a telecommunications node serving said plurality of mobile stations, comprising:

30 an application module for maintaining said plurality of first logical channels;

35 a processor for determining that the utilization of said plurality of first logical channels by some of said

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5        plurality of mobile stations has exceeded a threshold level associated with said telecommunications node; and a transmitter for transmitting, in response to said determination, first data informing such determination to said plurality of mobile stations.

10        15. The system of claim 14 wherein said first data further instructs said plurality of mobile stations to delay requesting low priority mobile services from said telecommunications node.

15        16. The system of claim 14 wherein said low priority mobile services include a Short Message Service (SMS).

20        17. The system of claim 14 wherein said low priority mobile services include a Unstructured Supplementary Service Data (USSD).

25        18. The system of claim 14 wherein said first logical channels comprise a Stand-alone Dedicated Control Channel (SDCCH).

30        19. The system of claim 14 wherein said first data are transmitted over a Broadcast Control Channel.

25        20. A mobile station for optimizing the utilization of a plurality of first logical channels for a high priority mobile service within a mobile telecommunications network, said mobile telecommunications network including a telecommunications node providing mobile service to said mobile station, comprising:

35        means for receiving a first indication indicating the availability of said plurality of first logical channels within said mobile telecommunications network;

35        means for receiving a second indication to request a mobile service towards said telecommunications node;

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means for determining that said requested mobile service has lower priority in comparison to said availability of said plurality of first logical channels; and

5 means for delaying said request for said mobile service towards said telecommunications node in response to said determination.

10 21. The mobile station of claim 20 wherein said first indication comprises data received over a Broadcast Control Channel.

15 22. The mobile station of claim 20 wherein said first logical channels comprises Stand-alone Dedicated Control Channels (SDCCHs).

23. The mobile station of claim 20 further comprising:

20 means for determining that current availability of said plurality of said first channels within said mobile telecommunications network is now able to handle said requested mobile service; and

25 means for requesting said mobile service towards said telecommunications node by requesting one of said plurality of said first logical channels.

